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CHEMICAL SYSTEMS LABORATORY

US Army Armament Research and Development Command
Aberdeen Proving Ground, Maryland 21010

TECHNICAL REPORT

ARCSL-TR-83066

POTENTIAL ENVIRONMENTAL IMPACTS OF ARMY LASER OPERATIONS: AN OVERVIEW

by

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Environmental Technology Division

June 1983

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ARCSL-TR- 83066	2. GOVT ACCESSION NO. AD-B077874L	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) POTENTIAL ENVIRONMENTAL IMPACTS OF ARMY LASER OPERATIONS. AN OVERVIEW		5. TYPE OF REPORT & PERIOD COVERED Technical Report 25 March 1982 - 30 June 1983 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Steven R. Bennett, Ph.D., CPT, MSC		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Commander, Chemical Systems Laboratory ATTN: DRDAR-CLT-I Aberdeen Proving Ground, Maryland 21010		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Commander, Chemical Systems Laboratory ATTN: DRDAR-CLJ-IR Aberdeen Proving Ground, Maryland 21010		12. REPORT DATE June 1983 13. NUMBER OF PAGES 117
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A

16. DISTRIBUTION STATEMENT (of this Report)

Distribution limited to US Government agencies only because of test and evaluation; June 1983. Other requests for this document must be referred to Commander, Chemical Systems Laboratory, ATTN: DRDAR-CLJ-IR, Aberdeen Proving Ground, Maryland 21010.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Environmental impacts
Lasers
Laser radiation
Laser hazards
Laser safety standards

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Lasers have become increasingly useful in military operations, particularly as aids for training, acquisition of targets, and fire control. This document addresses environmental impacts attending Department of Army research and development programs of military utility. It is intended to provide relevant background information for Army environmental documentation requirements as detailed in Army Regulation (AR) 200-2 and supplements to this AR by the major Army commands.

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PREFACE

The work described in this report is one of the programmatic environmental analyses authorized by the Department of the Army Materiel Development and Readiness Command.

The use of trade names in this report does not constitute an official endorsement or approval of the use of such commercial hardware or software. This report may not be cited for purposes of advertisement.

Acknowledgments

Sincere appreciation is extended to Messrs. D. H. Sliney and T. Lyons, US Army Environmental Hygiene Agency, and Mr. J. Mosovsky, Lawrence Livermore National Laboratory, for permission to include published and unpublished material.

I am grateful to COL E. Beatrice, Drs. H. Zwick and D. Randolf, and Mr. B. Stuck, Letterman Army Institute of Research; Messrs. J. Paul and L. Fillian, US Army Night Vision and Electro-Optics Laboratory; Dr. G. Dezenberg, Army Missile Laboratory; MAJ D. Parmer, US Army Test and Evaluation Command; and Mr. J. Tragesser, US Army Materiel Development and Readiness Command, for their contributions and counseling.

My colleague, Mr. D. J. Wenz, Environmental Technology Division, Chemical Systems Laboratory, worked tirelessly to gather and analyze much basic data and information.

Finally, special thanks is given to Cecilia Doughty for her professional and timely editorial assistance and to Lisa North for her exemplary patience and word processing capability during revisions of this document.

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AN OVERVIEW

1. INTRODUCTION

The term "laser" is an acronym for Light Amplification by Stimulated Emission of Radiation. Quite simply, a laser is a device that strengthens or amplifies light to produce a very narrow, intense beam which is transmitted in one direction. Many materials have been shown to be capable of emitting laser light, some at intensities several hundred times brighter than sunlight.

The unique properties of laser light and lasing devices (see Appendix A) are useful in many technologies, including communications, precision measurement, guidance systems, welding, photography, and medicine. Lasers have become increasingly useful in military operations, particularly as aids for training, the acquisition of targets, and fire control. The potential of certain lasers to accurately transfer huge amounts of energy to small areas is also of interest for future weapons systems. Because of the likely importance of lasing devices in future military battlefields, laser research is actively supported by the Department of Defense (DOD) with programs under the direction of the Department of the Army (DA) and the other military services.[1]

This document addresses potential environmental impacts attending DA research and development programs for laser technologies of military utility. It is intended to provide relevant background information for Army environmental documentation requirements, as detailed in Army Regulation (AR) 200-2[2] and in supplements to this AR by the major Army commands (MACOMs). Because of the large variety of potential applications for military lasers, emphasis is placed on environmental risks attending development of general laser technologies rather than of specific lasing devices.

Much about Army laser research is classified defense information (see AR 380-2[3] and AR 380-6[4] regarding security classification guidelines for laser systems). All information used for this document can be obtained from the open literature or from unclassified government reports.

2. ARMY LASER PROGRAMS

2.1 History and Organization.

Military interest in laser research can be traced to the pioneering work of Townes at Columbia University in the 1950's,[5,6] which was funded in part by the DOD Joint Services Electronics Program. The first military application of this technology was demonstrated in a prototype rangefinder in 1962. Since then laser and related technologies have introduced combat capabilities to military forces that promise to radically alter traditional concepts of conventional warfare.[7,8,9]

Programs for development and deployment of laser devices are found at many levels within DOD (see Figure 1). Within the DA, responsibility for research, development, and evaluation of laser technologies is organized into low energy and high energy laser systems.* Responsibility for most basic low energy laser research is assigned to the Night Vision and Electro-Optics Laboratory, US Army Electronic Research and Development Command, Fort Belvoir, Virginia; High energy laser (HEL) research is managed by the Directed Energy Directorate, Army Missile Laboratory, US Army Missile Command, Redstone Arsenal, Alabama. All military high energy laser programs are also coordinated at the Office of the Secretary of Defense.

Army research on environmental effects of laser radiation is found in programs managed by the US Army Medical Research and Development Command's Letterman Army Institute of Research (LAIR),** and the USA Electronic Research & Development Command's Atmospheric Sciences Laboratory (ASL).† Workers at LAIR are investigating biological effects of acute and subacute laser irradiation, particularly on skin and ocular tissues. Results of this work are used to regulate potential exposure risks to military personnel. ASL is the Army's lead laboratory for meterological support of ground based HEL programs at the National High Energy Test Range at White Sands Missile Range (WSMR), New Mexico, and is investigating laser propagation in the atmosphere.

Other federal agencies are currently funding laser research of potential value to Army needs. Examples include Department of Energy (DOE) programs in laser fusion and isotope separation, and National Aeronautics and Space Administration (NASA) research in space communications. Army laser research has also benefited over the years from collaborations with industry and academia as evidenced by technological advances with widespread civilian and military applications (see Table 1). Such research at major university and industrial research facilities is funded by research offices and developmental laboratories of the military services.

*The distinction between low and high energy lasers is somewhat arbitrary. From the military systems perspective, low energy laser technology addresses all laser applications with the exception of high energy laser (HEL) weapons. HELs are defined as any laser with an average power exceeding 20 kilowatts or a single pulse energy of 30 kilojoules or more. However, a laser is considered to be "high power" (capable of producing injury to skin) by health and safety criteria (see Appendix D) if it is capable of an average power of at least 0.5 watt for 0.25 seconds or more.

**Division of Ocular Hazards, Letterman Army Institute of Research, Presidio of San Francisco, California 94129

†Propagation Research Branch, Atmospheric Sensing Division, Atmospheric Sciences Laboratory, White Sands Missile Range, New Mexico 88002.

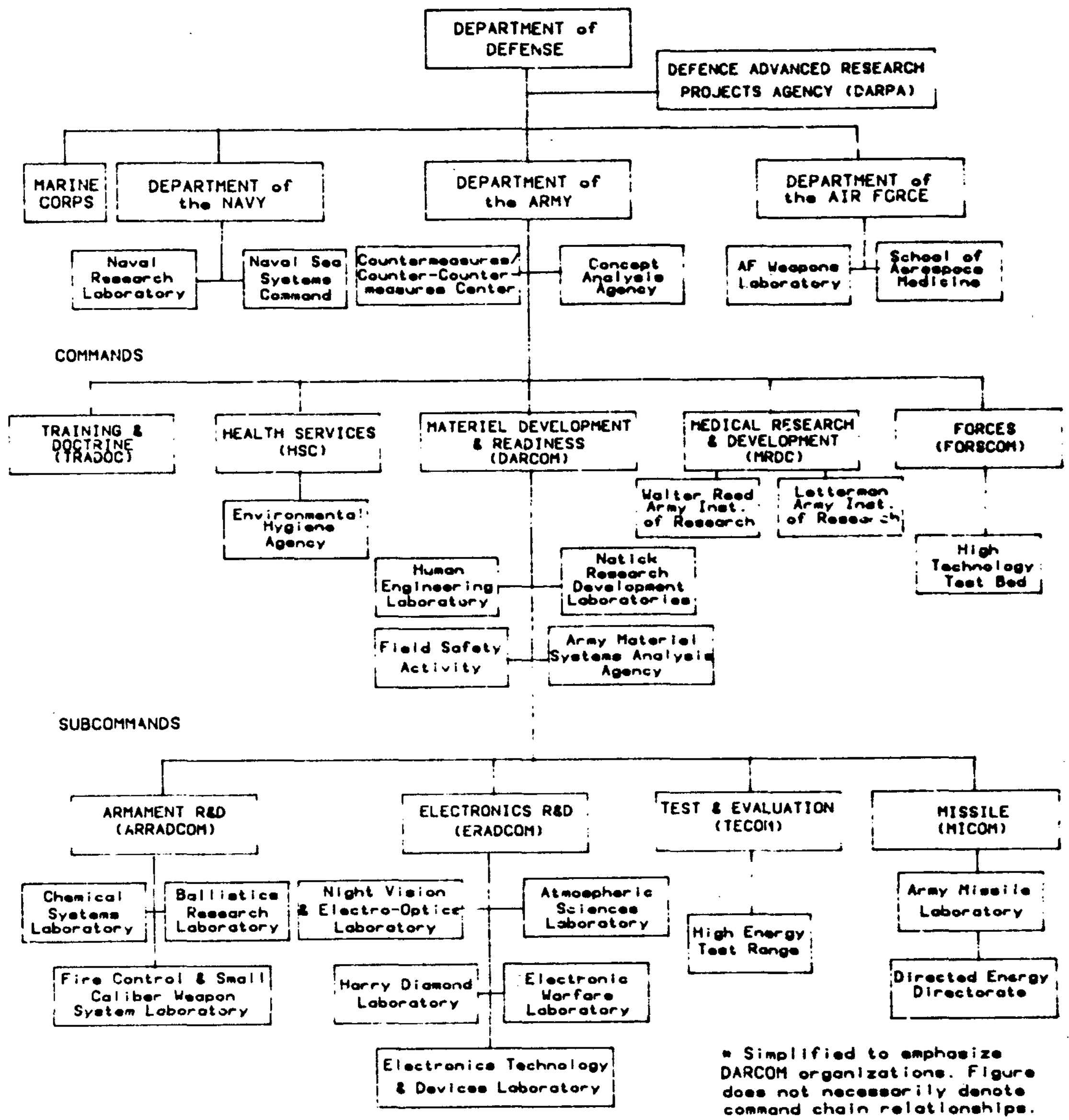


Figure 1. Organization Chart of Department of Defense Laser Activities

Table 1. Military and Civilian Applications of Laser Technology

DOD Application	Civilian Application
Communication/fiber optics	Multi-channel telephone/TV links
Laser sensors	Laser gyros for airplanes
Micro meteorology Shear measurement for air	Visibility/cloud height meter, wind safety
Chemical agent detection	Pollution detection and control
Material preparation	Various areas of industrial production
General laser sources	Medical applications/ entertainment/education/ transportation/law enforcement

2.2 Applications of Army Laser Technologies.

2.2.1 Research and Development.

2.2.1.1 Fire Control and Weapons Guidance.

To date, the majority of fielded Army lasing devices have been used to detect and mark military targets. Targets can be illuminated by laser light from devices (rangefinders) which also measure reflection times from the target to accurately determine distances between target and observer. Other lasing devices can be used to mark or "designate" targets for incoming sensor-equipped (smart) munitions.

2.2.1.2 Communications.

One of the most promising applications of laser technology is in the field of communications, where laser frequencies have the potential to greatly exceed the information-carrying capacities of lower frequency radiowave and microwave systems. Military advantages of optical transmission frequencies include increased variety and security of communication networks and improved efficiencies for long-range transmissions.

Army programs in this field include development of semiconductor injection laser technologies for guided optical communication (fiber optics) systems and for short- to medium-range (line-of-sight) communicators. Developments in glass fiber research have established the need for laser transmissions at wavelengths near 1.5 microns. Current research is designed to produce semiconductor alloys capable of effective output in this range.

2.2.1.3 Training Aids.

It is desirable that military personnel be trained to use modern weaponry under realistic battlefield conditions. Toward this end a semiconductor (gallium arsenide, GaAs) laser has been developed and incorporated into a training system, the MILES,* which simulates weapons firing during training and field exercises. The MILES and other laser-based training aids are effective, but necessarily result in greater risk of human exposure than other laser systems. Current programs in this area are designed to improve the reliability and safety of these systems. Eye-safe solid-state lasers are also being improved to enhance training applications for hand-held rangefinders and other fire control systems.

*Multiple Integrated Laser Engagement System

2.2.1.4 Remote Detection.

Certain properties of reflected light can be analyzed to yield information about the medium through which the light is propagated. Lasers, particularly those emitting in the infrared (IR) spectrum, are potentially useful as remote atmospheric probes for meteorological investigations. Current work in LIDAR (Light Detection and Ranging), an optical radar, may result in remote sensing capabilities for atmospheric pollutants, including potential nuclear, biological, and chemical particulates and aerosols. Other advanced systems are being developed to improve current military surveillance capabilities.

2.2.1.5 Weapon Systems.

Laser radiation can potentially be used in weapon systems (Directed Energy Weapons) to damage military targets. Damage would occur when enough electromagnetic energy is transferred to a target to cause it or one of its critical components to malfunction by overheating.

Three types of HEL technologies (gas dynamic laser, GDL; electric discharge laser, EDL; chemical laser, CL) are potentially suitable for weapon applications. A fourth system, the free-electron laser (FEL), may also have important applications but is not advanced enough technologically for full appraisal. Although capable of output in the kilowatt (or kilojoule) range or higher, each of these lasing systems is currently beset with significant limitations regarding military utility. Work in this area will require large investments and years of research and development before any HEL weapon system can be fielded.

2.2.1.6 Other.

In addition to the applications discussed above, Army interests in laser technology also include uses in data processing (holography), isotope physics (high-speed laser spectrography), and materials technology (machining, welding). A summary of these and other applications is given in reference 1 and Table 2.

2.2.2 Training and Testing Facilities.

Army lasers are being used at several military installations throughout the United States (see Table 3). Activities vary from research and testing of new systems to large scale training exercises with fielded equipment (MILES, rangefinders). All laser ranges are designed in accordance with guidelines in AR 385-63[10] to limit wayward transmissions of laser radiation.

Perhaps most important from an environmental viewpoint is the National High Energy Laser System Test Facility (HELSTF) at WSMR. This facility is scheduled to become operational during FY83 and is specifically designed to test and evaluate high energy laser systems within the DOD. Additional information about this facility is provided elsewhere.[11,12]

Table 2. Army Applications of Laser Technologies

Field of Application	Laser	DOD Systems
Remote line-of-site meteorology	Solid-state	Visibility, aerosol, and wind field measurements
Chemical/biological agent/ exhaust detection	Gas, semiconductor	LIDARs
Advanced laser sensors	Gas, semiconductor	Laser gyros; acoustic sensors
Data processing	Semiconductor	Fourier transform via integrated optics/acousto-optics devices/optical storage
Laser material preparation	Solid-state, gas	Marking, cutting, drilling, annealing
Laser-directed energy weapons	Chemical, gas-dynamic electron discharge	Feasibility demonstration
		1st Generation Systems
Fire control and weapons guidance	Solid-state	Rangefinders Designators
		2nd Generation Systems
	Gas	Beamriders Active smart sensors Laser/mm wave hybrids
Laser surveillance/radar	Gas, semiconductor	Passive/active FLIRS 3-dimensional airborne line scanners Underwater detection
Communication and information transfer	Semiconductor	High bandwidth fiber-optics communication
Training aids	Semiconductor	Battlefield simulation

Table 3. Approved Army Laser Ranges*

Location	Classification** Activity	Objective
Ft Monmouth, NJ	I, O, G	R&D,
Picatinny Arsenal, Dover, NJ	I, O, G	R&D
Aberdeen Proving Ground, MD	I, O, G	R&D
Ft A.P. Hill, VA	O, G	R&D
Ft Bragg, NC	O, G, A	R&D, T
Ft Benning, GA	O, G	R&D, T
Ft Stewart, GA	O, G, A	T
Redstone Arsenal, AL	I, O, G, A	R&D, T
Ft Knox, KY	O, G,	T
Ft Campbell, KY	O, G, A	T
Ft Polk, LA	O, G	T
Ft Riley, KS	O, G	T
Ft Sill, OK	O, G	R&D
Ft Hood, TX	O, G, A	R&D, T
Ft Bliss, TX	O, G, A	R&D
Ft Carson, CO	O, G, A	R&D, T
White Sands Missile Range, NM	I, O, G, A	R&D
Ft Huachuca, AZ	O, G, A	R&D
Yuma Proving Ground, AZ	O, G, A	R&D
Ft Irwin, CA	O, G	T
Ft Hunter - Liggett, CA	O, G, A	R&D
Yakima Firing Center, WA	O, G, A	R&D
Ft Lewis, WA	O, G	T

*Compiled from information supplied by Messrs. T. Lyon and D. Sliney, US Army Environmental Hygiene Agency, Aberdeen Proving Ground, MD 21010

**I = indoor, O = outdoor, G = ground, A - air, R&D = Research and Development, T = Training

2.2.3 Production.

The development, deployment, and disposal (life cycle) of Army equipment and weapons are governed by its system of materiel acquisition, as detailed in AR 1000-1[13] and other publications.[14] This process varies somewhat with each system under development but is designed to insure that items acquired by the Army are thoroughly evaluated before being deployed.

Once a system has been type-classified (listed in the Army inventory), production plans are prepared for initial purchases and, following validation of initial production runs, items are shipped to appropriate users. Major Army procurement actions entail a decision process, called "make-or-buy," in which commercial and military production costs are estimated and compared. To date, all type-classified laser systems have been produced on contract by industry, and it is likely that industrial (rather than military) production resources will be employed for future systems as well.

2.2.4 Demilitarization and Disposal.

When Army equipment is no longer useful or becomes too expensive to operate and maintain, it is demilitarized in accordance with established DOD procedures, which are designed to salvage and recycle as many militarily unique materials as possible.[15] Other materials are either sold to industry or disposed of.

Demilitarization and disposal procedures for laser systems will vary with the design and type. Requirements for disposal of exempted military lasers (see 2.3) are provided in AR 385-9[16] Typically, metal and other structural materials would be incinerated and sold as scrap. Chemical components (e.g., coolants, dyes) would be drained and incinerated or otherwise appropriately disposed of (see 2.4, below); containerized gases and electrical components would be salvaged and/or recycled as required.

2.3 Health and Safety.

Laser products must normally comply with Radiation Safety Performance Standards of the US Food and Drug Administration (21 CFR, part 1040.1, subchapter J - Performance Standards for Light-Emitting Products). Certain military laser products, i.e., lasers designed for combat or combat training operations, have been exempted from these standards in some cases (FDA Exemption No. 76 EL-01 DOD). These exempt military laser products and associated equipment (e.g, rangefinders, target designators, radars, direct-fire weapons) are subject to other military regulations and standards.* Military lasers for noncombat applications (e.g., surveying, medical, general communications) are subject to requirements of the FDA standard.

Army policy and procedures for control of health hazards from lasers and other high-intensity optical sources are given in AR 40-46.[17] Other important guidelines include TB MED 279[18] (assessment of laser health hazards), AR 385-63[10] (range safety protocols), AR 385-9 (handling of military exempt lasers)[16] and Department of the Army

*A draft military standard, "Safety Design Requirements for Military Lasers and Associated Equipment," has been prepared and is awaiting approval.

Materiel and Readiness Command (DARCOM) Regulation (DR) 385-29[19] (laser safety requirements at DARCOM facilities). These regulations are summarized briefly below and should be consulted for more detailed information.

The Surgeon General, Department of the Army, is responsible for evaluation of potential hazards to Army personnel from lasers and other sources of optical radiation. This responsibility is discharged through the US Army Environmental Hygiene Agency* which conducts comprehensive surveys of lasing devices at Army facilities and reviews laser safety programs of the major Army commands.

Hazard controls for laser radiation depend on the type of laser and its usage. For example, lasers are classified by output level into several hazard categories (see Appendix C), which range from devices incapable of hazardous radiation (Class I) to high power lasers capable of producing fire and skin hazards (Class IV). In addition, protection standards are specified in AR 40-46 for permissible exposure levels of ultraviolet (UV), visible, and IR radiation to human eyes and skin.[17] These standards are used in turn to design and operate test ranges and other facilities where lasers are employed.

Other potential health and safety hazards will vary with the type of laser being used and may include exposure to excessive noise; airborne contaminates; toxic, flammable, or corrosive chemicals; electrical shock; and ionizing radiation (e.g., x-rays). Safety guidelines for these hazards are provided annually in publications of the American Conference of Government Industrial Hygienists (ACGIH),[20] and also in Army System Safety Programs, as required by Military Standard 882 (Systems Safety Program Requirements) to identify and control hazards for specific laser products under development.

2.4 Environmental Laws and Regulations.

Environmental laws and regulations are of two types: (a) those requiring assessment of environmental impacts of specific programs or actions, and (b) those requiring compliance with environmental pollution standards. In addition to the federal laws and regulations mentioned below, each state and nearly all municipalities have laws or ordinances regulating the storage and transportation of hazardous substances within their jurisdiction. Although laser radiation is an unlikely source of environmental pollution, per se, chemicals and facilities associated with the operation of laser systems may be affected by one or more of the statutory requirements listed below. The primary purpose of this section is to identify general features and applications of those environmental regulations most likely to influence lasing systems during their life cycle. Specific applications will vary with individual items, and should be addressed accordingly.

2.4.1 National Environmental Policy Act.

The National Environmental Policy Act of 1969 (NEPA) was created by Congress to establish a national policy to protect the environment and to minimize adverse environmental consequences by requiring that impacts of planned federal actions

*Directorate of Radiation and Environmental Sciences, HSE-RL, Aberdeen Proving Ground, MD 21010

and alternatives be evaluated before being undertaken. As currently implemented,[21] this act is binding on activities of all federal agencies except where inconsistent with other statutory requirements. Certain provisions of NEPA are also incorporated into other federal legislation, including the National Historic Preservation Act of 1966 and the Endangered Species Act of 1973.

Army policy in NEPA matters is provided in AR 200-2,[2] which establishes responsibilities and procedures for integration of environmental considerations into Army planning and decision making. Among these responsibilities are the identification and analysis of environmental risks for proposed actions and their most likely alternatives. The policy of DARCOM requires environmental analysis and documentation for all items (including lasing devices) being developed under its program/project/production managers and research and development commands.[77] In addition, site-specific environmental documentation may be required for training and other exercises in which lasers are involved.

2.4.2 Resource Conservation and Recovery Act.

The Resource Conservation and Recovery Act of 1976 (RCRA) established a national program for management of waste, including hazardous waste (40 CFR parts 260-65; 267). Wastes are defined by RCRA as "hazardous" if specifically listed by regulation or if exhibiting any one of the characteristics of reactivity, corrosivity, ignitability, or toxicity (as defined in 40 CFR, 261.2). The present Environmental Protection Agency (EPA) list includes approximately 400 chemicals and 85 process wastes. State regulations may also impose requirements not present in federal regulations.

Under the RCRA, the generator of waste must determine whether or not it is hazardous. If found to be hazardous, the waste is then subject to comprehensive "cradle to grave" record keeping requirements, including a manifest system to track and document the generation, transportation, and ultimate disposal of the material in a permitted facility for the management of hazardous waste. It should be emphasized that substances are not classified by RCRA as wastes until they are ready to be discarded. The regulations do not apply to the reuse, recycling, or reclamation of hazardous wastes, except that hazardous waste sludges and listed hazardous wastes are subject to certain requirements respecting transportation and storage (40 CFR 261.6).

Substances identified by the EPA under the RCRA as "acute hazardous" and "toxic" wastes are listed in 40 CFR, part 261.33. Other substances, i.e., liquid dyes, may qualify as a hazardous waste by exhibiting one or more of the characteristics described above (see 3.2.1).

2.4.3 Toxic Substance Control Act.

The Toxic Substance Control Act of 1976 (TSCA) addresses the manufacture, importation, distribution, and use of chemical substances. As implemented by 40 CFR, parts 704-710, this act authorizes the EPA to inventory commercial chemicals and, for chemicals listed after 31 December 1979, to require sufficient data to estimate health and environmental hazards of production and use.

The reporting and testing requirements of the TSCA will only affect Army laser programs if chemical substances used for laser research are unlisted on the revised 1979 TSCA inventory (45 FR 505444, 29 July 1980) and/or are imported or produced primarily by the Army for its purposes.

2.4.4 Clean Air Act.

The Clean Air Act of 1963 (CAA) was created because of public concern over health problems associated with air pollution. As currently implemented (40 CFR, parts 50-52), the CAA authorizes a comprehensive regulatory program to achieve specific National Ambient Air Quality Standards (NAAQS). The EPA has promulgated NAAQS for certain pollutants, including sulfur dioxide (SO_2), total suspended particulates, photochemical oxidants, carbon monoxide (CO), nitrogen dioxide (NO_2), and hydrocarbons. These standards define the quality of air that must be achieved and maintained to prevent adverse effects to national air resources and were prepared specifically to protect human health and the quality of the environment. It is recognized that adverse effects can occur from brief exposures to high levels of pollution, or from long-term exposures to lower levels of pollution. Consequently, most NAAQS specify two types of limitations - long-term standards which cannot be exceeded on an annual average and short-term exposures which cannot be exceeded for brief periods (e.g., 3 hours and/or 24 hours).

Under the CAA, the country is divided into 247 air quality control regions (AQCRs) to provide basic geographical units for air pollution control. States are required to prepare State Implementation Plans to implement and enforce criteria pollutant standards in those regions. State standards are often more stringent than federal standards and vary from one AQCR to another.

Among Army lasers, only certain HEL systems, particularly HF/DF chemical laser designs, are potential sources of significant air pollution. The significance of air emissions from these sources would be influenced, however, by several factors, including geographic location, activity, and design of the lasing devices (see 3.2.1).

2.4.5 Other Federal Regulations Governing Release of Hazardous Substances into the Environment.

Policies and procedures for control of discharges of oil and hazardous substances into the environment are detailed in the Federal Water Pollution Control Act of 1972 (FWPCA) as implemented[23] and the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA).[24] Section 311 of the FWPCA describes requirements for handling spills of oil and hazardous substances. A "spill" is defined as the release or discharge of regulated pollutants not covered by permit by pumping, pouring, emitting, emptying, leaking, or dumping. The EPA has promulgated regulations under the FWPCA which identify and establish reporting requirements for approximately 270 hazardous substances. Reporting requirements are based on harmful quantities as defined by the regulation.

The CERCLA establishes reporting requirements for the release of hazardous substances into the environment, including land, air, and water when release occurs in amounts equal to or greater than the reportable quantity. As defined by the CERCLA, a hazardous substance is any substance designated or listed in the FWPCA, Sections 307 and 311; the RCRA, Section 3001; the CAA, Section 112; and the TSCA, Section 7. "Reportable quantities" for any of these substances is one pound, unless otherwise specified in Section 311 of the FWPCA.

2.4.6 Transportation of Hazardous Materials.

The US Department of Transportation is required by federal law to formulate regulations for safe transportation of hazardous materials, poisonous substances, explosives, and other dangerous articles (49 CFR, parts 171-177). These regulations bind all carriers engaged in the transport of the above mentioned hazardous material and are in accordance with the best known practices for assuring safety in transit. Of particular importance is part 172 of these regulations which lists hundreds of materials by hazard class (e.g., "flammable," "corrosive") with guidelines for safe packaging and shipping. Additional guidance is provided elsewhere.[25]

2.4.7 Military Installations.

Policies and procedures for environmental protection of Army installations are provided in AR 200-1,[26] "Environmental Protection and Enhancement." This regulation describes Army environmental management objectives in several important areas, including air pollution and water resources, solid and hazardous wastes, toxic and hazardous materials, noise abatement, and contingency plans for spills of oil and hazardous substances. Additional guidelines are provided in respective supplements to this regulation from MACOMs and installations.

Requirements for shipment and storage of military items and hazardous materials are provided in other Army regulations.[27,28,29]

3. POTENTIAL ENVIRONMENTAL IMPACTS

3.1 Laser Radiation.

3.1.1 Biological Effects.

Light interacts with living matter in many ways and is the environmental component of the biological phenomena of vision, photosynthesis, and photoperiodism (the cyclical response of animals and plants to day length and darkness). These important life processes ultimately depend upon interactions of light with specific pigments and are functions of wavelength, intensity, and duration of exposure.[30]

Adverse effects of laser light are known, or assumed, to be similar to those of other sources of optical radiation. It should be noted, however, that knowledge of laser effects in biological systems is based largely on experiments with laboratory mammals (primarily rodents, rabbits, and primates) to establish exposure thresholds for safety of human eyes and skin in industrial and military settings. Effects of laser radiation on other vertebrate species, invertebrates, plants, and microorganisms are largely unstudied and must be inferred from available evidence of biological interactions with other sources of optical radiation.

3.1.1 Terminology.

An understanding of certain photometric and radiometric terms is helpful when discussing biological exposures to optical radiation[18,31] (see also Appendix B). Photometric units (e.g., lumens, candelas, lux) are weighted to the spectral response of the human eye. Because human vision is insensative to most UV and IR radiation, photometric units are unsuitable to address biological hazards from exposures to these wavelengths.

Radiometric terminology, on the other hand, is expressed in physical units. Among the most commonly used terms for laser exposures are radiant power, radiant energy, radiance, irradiance, and radiant exposure. Radiant power (or radiant flux) and radiant energy are used to specify strengths of continuous (in watts) or pulsed (in joules) optical sources, respectively. Radiance is essentially a measure of brightness. To describe the radiance of a source, it is necessary to know both the concentration of light reaching the eye (in watts-per-square-centimeter (w/cm^2)) and the solid-angle in space from which it arrives. Radiance is used to discuss effects of light focused at an image plane and thus is useful to describe retinal hazards.*

Irradiance and radiant exposure are used to describe radiant power arriving at a surface (as opposed to leaving a source). Irradiance exposure rates are typically in watts (milliwatts, microwatts) per-square-centimeter (w/cm^2). Radiant exposure, the product of average irradiance and exposure duration (in seconds), is a measure of total dose, or accumulated exposure, and is typically expressed in joules (millijoules, etc.) per-square-centimeter (j/cm^2).

3.1.1.2 <u>Animals.</u>

Mechanisms of laser injury to animal tissues are not fully understood, but can be classified generally as either photochemical or thermal in nature.[31] Photochemical injury is associated with UV and short-wavelength visible (i.e., blue-green) radiation (where photon energies are greatest) and can occur at low irradiances delivered over extended periods of time. Radiant exposure levels for photochemical injury are typically constant for exposure durations ranging from microseconds to hours ("reciprocity"). Thermal injury will generally occur only after momentary (as opposed to prolonged) exposure to pulsed lasers and can involve IR and radiation of shorter wavelengths. Radiant exposure levels for thermal injury are not "reciprocal" and are influenced by several factors, including tissue capacity to conduct heat. Specific effects of optical radiation to eyes and skin are discussed briefly below and in Appendix C. More detailed information can be found in other references.[20,32,33,34,35]

<u>Eyes</u> - The eye is the organ of vision and is structured to focus light onto visual pigments as images, which are transmitted and interpreted by neural pathways of the brain. Because of its capacity to focus incident light (optical gain of up to 100,000x for point sources), the eye is the most sensitive of animal structures to injury by laser radiation.[18,36,37]

Optical radiation is absorbed differentially by wavelength as it passes through the eye. For example, most high energy radiation (e.g., x-ray, gamma ray) passes completely through ocular tissues with little absorption. Short UV (UV-B, C) and far IR (IR-B, C) are absorbed principally at the cornea and lens. Visible and near IR (IR-A) radiation is refracted at the cornea and lens and absorbed in the ocular media (IR-A) and at the retina.[18,36] It should be noted that the retinal photoreceptor rod cells most responsible for human night vision (scotopic vision) are more sensitive to shorter visible

*For example, laser light with a radiant power of 1 microwatt will produce a brightness within the eye that is much greater than that of a milliwatt beam (1000 times more power) from a conventional (e.g., diffuse) light source. The high radiance of laser light is the reason for its potential as an ocular hazard.

wavelengths (peak sensitivity at 500 nm) than the daylight-sensitive (photopic) cone cells (peak sensitivity at 550 nm).[32,38]

Potential eye injuries from laser radiation are summarized in Figure 2 as a function of wavelength. Injury will vary with the duration and intensity of exposure from mild discomfort to permanent impairment.[32,36,39] For example, thresholds for corneal injury from far IR (e.g., CO_2 laser) radiation have been observed to increase by almost a factor of 10 (from 0.2 to 1.5 J per cm^2) with increased durations of exposure (from milliseconds to seconds). The human blink reflex offers protection from such challenges, especially at visible wavelengths, but requires about 0.2 second to occur. Risks of eye injury are greatest, therefore, for lasers (e.g., pulsed lasers) that are able to exceed injury thresholds within this exposure period.[17,32,40]

Present eye safety standards are based largely on observed changes to ocular structures following acute exposures to laser radiation (see Appendix C). Potential hazards of chronic exposure, particularly from IR wavelengths, are less well known.[37,39] Recent work, however, suggests that primate vision may be altered following prolonged low level exposures to visible laser light above 500 nm.[41,42] These effects may be related to coherent properties of laser light and have been observed at retinal irradiances below those for incoherent monochromatic light under similar conditions.[43,44] Other findings indicate wavelength dependence of the retinal response to exposures in the near IR, heretofore unanticipated, which suggests that current exposure guidelines in this spectral region may have to be reappraised.[45]

Risk of ocular injury is greatest for humans and other animal species when laser light of visible or near IR wavelengths is focused onto the sensory retina. In humans and other primates a structure, the fovea, is comprised of concentrated photoreceptor cells for enhanced visual activity and perception of color.[46] Foveae or structures with similar functions have been identified in other vertebrate classes, including many fish, reptiles, and birds, particularly birds of prey.[47] Other nonprimate ocular structures may also influence risks of injury from laser exposures. One such adaptation, the tapetum lucidum, occurs in eyes of many nocturnal species and apparently improves vision in dim illumination by reflecting incident light more efficiently onto visual receptor cells.[38] Other adaptations enable eyes of certain vertebrates to gather more light at greater angles of incidence than primate eyes. Vertebrate retinal pigments have adapted to different wavelengths within the "visible" spectrum, but not, apparently, to wavelengths significantly beyond primate eye limitations in the UV and IR region.[38] In contrast, invertebrate vision, particularly among terrestrial arthropods, is generally more sensitive to UV (UV-C) and less sensitive to longer wavelengths (e.g., beyond 600 nm) than vertebrate eyes.[47,48] Considered alone and in the absence of experimental data, these phenomena and their relationships to laser exposure hazards are difficult, if not impossible, to assess accurately for other animal species. Until such assessments are available, it seems prudent to evaluate all potential ocular hazards from laser radiation in animals in terms of standards for human exposure.

Skin - Skin both protects and helps mediate responses to environmental challenges (e.g., extremes of temperature, radiation, moisture, physical and chemical trauma).[49] It is composed of two layers, an outer stratified nonvascular epidermis and an inner dermis, or corium, of vascular and connective tissues. In addition to the functions mentioned above, dermal tissues are the source of various structures (hair, feathers, scales, horns, nails, glands) which are responsible for animal appearance and odor, and thus of sensory cues which underlie many important intra - and interspecific behavioral traits.

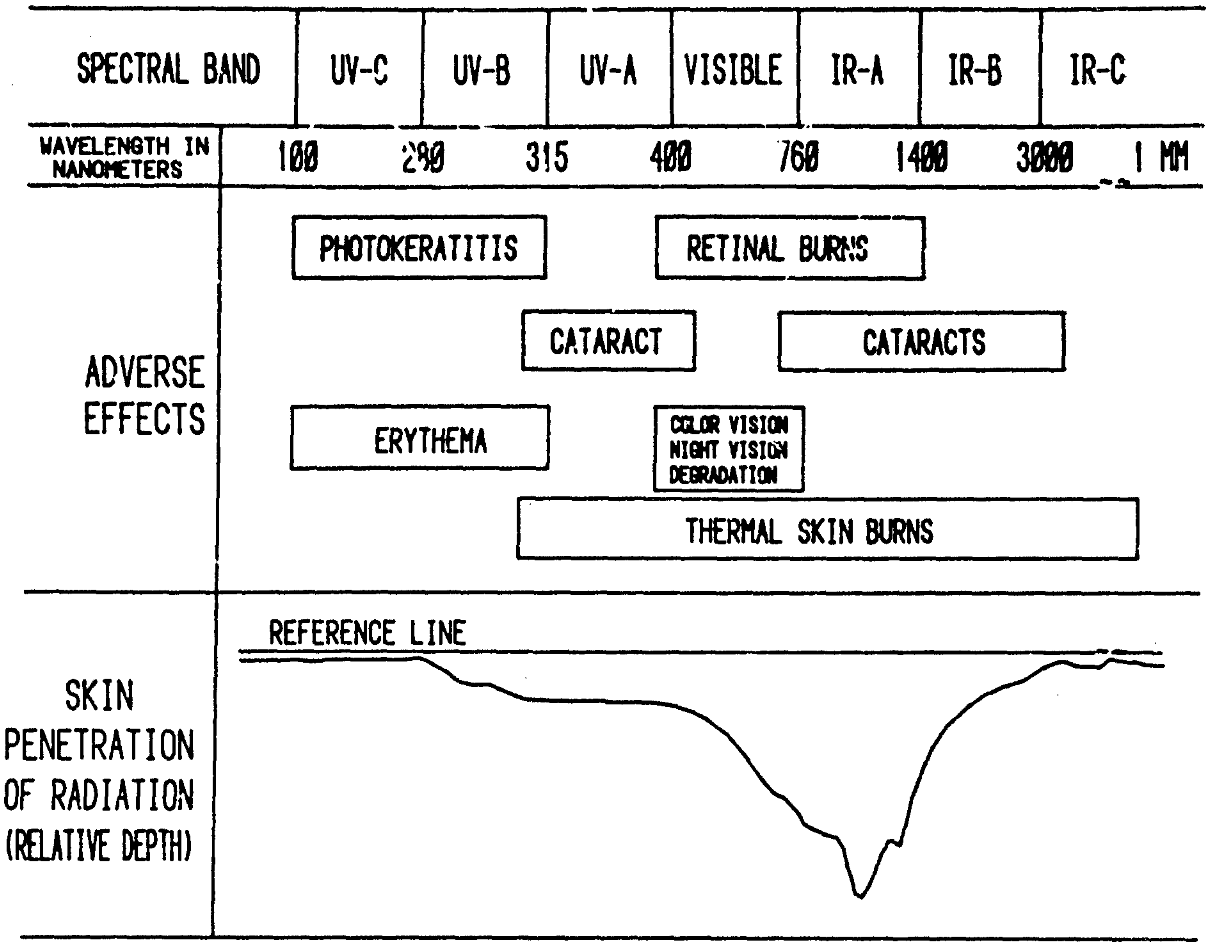


Figure 2. Acute Effects of Optical Radiation to Eye and Skin Tissues, by Spectral Band* (modified after Sliney[29])

*Spectral Band Designations of the Internal Commission on Illumination (CIE)

Although nonthermal skin reactions (e.g., blistering, sunburn) are possible from short UV (UV-B, C) radiation, most laser-induced skin injury is believed to involve thermal responses to wavelengths longer than 315 nm.[20,35] Mechanisms of thermal injury depend largely on the duration and area of exposure and on the capacity of the body to withstand thermal stress. Thermal injury can also be studied as a function of irradiance or radiant exposure levels from a powerful light source. Skin injuries from such exposures are termed "flash burns," and can occur following even momentary exposures to focused high-power carbon and xenon arcs, or to certain CW lasers. For example, irradiances from carbon-arc (white light) exposures of 0.5 s to 2 cm^2 patches of skin were shown to cause first-degree burns (mild reddening or erythema) at 12 w/cm^2, second-degree burns (blistering) at 24 w/cm^2, and third-degree burns (destruction of the epidermis) at 34 w/cm^2.[30] For smaller areas of skin, heat would be more effectively conducted by irradiated tissues, and thus greater irradiances would be required for similar levels of thermal injury. Likewise, lower exposure levels would be required if larger body areas were irradiated.[32]

Effects of exposure duration on first-degree thresholds for thermal injury are shown in Figure 3 for several irradiances of IR (CO_2) laser and white light. The lower injury thresholds for far IR laser radiation depend in part on the capacity of the skin to absorb and reflect incident radiation of different wavelengths. Figure 4 illustrates typical reflectances of darkly and lightly pigmented human skin. Note in each case the low reflectance (high absorbance) at UV and far IR wavelengths. It can be seen in Figure 2 that visible and near IR wavelengths are absorbed deeper into dermal tissues than IR wavelengths (e.g., beyond 2 μ m). Thus, risks of thermal injury are likely to be greater for exposures to far IR wavelengths, which transfer more heat energy to smaller masses of tissue, than to shorter wavelengths of the optical spectrum.

Sensations of heat and pain are also related to dermal injury thresholds, both being functions of temperature. Persistent pain in humans is elicited at skin temperatures above 45°C, a temperature tolerated without tissue injury for several seconds.[40] Thus, injury can sometimes be avoided if exposed areas are quickly removed or shielded from the source of radiation. Escape responses of this nature are more likely to occur following exposure to CW lasing sources. Exposures to high energy laser pulses of short (e.g., nanosecond or picosecond) duration will tend to damage cells by nonthermal mechanisms (before thermal equilibria are reached) so that injury may already have occured when pain is first experienced. This is particularly true of far IR radiation, which is less readily perceived as pain than shorter wavelengths.

Potential dermal hazards to other animals will vary with the reflectance and heat absorption profiles of their respective dermal tissues. When the skin of animals is covered by fir, feathers, scales, and other structures, absorption profiles are likely to vary signficantly from those of human skin, but because these dermal derivatives have typically lower water contents than living skin, they would probably absorb and conduct heat more efficiently to living dermal tissues.

3.1.1.3 Plants.

Plants are subjected daily to electromagnetic radiation over the entire frequency spectrum. The most important wavelengths for plant growth and stress, however, are found in the spectral region from mid UV (UV-B) to the near IR. Effects of mid and far IR (IR-B, C) radiation are essentially thermal, much like those described previously for animal systems, and will result in burns or water stress depending upon incident irradiances and areas exposed.

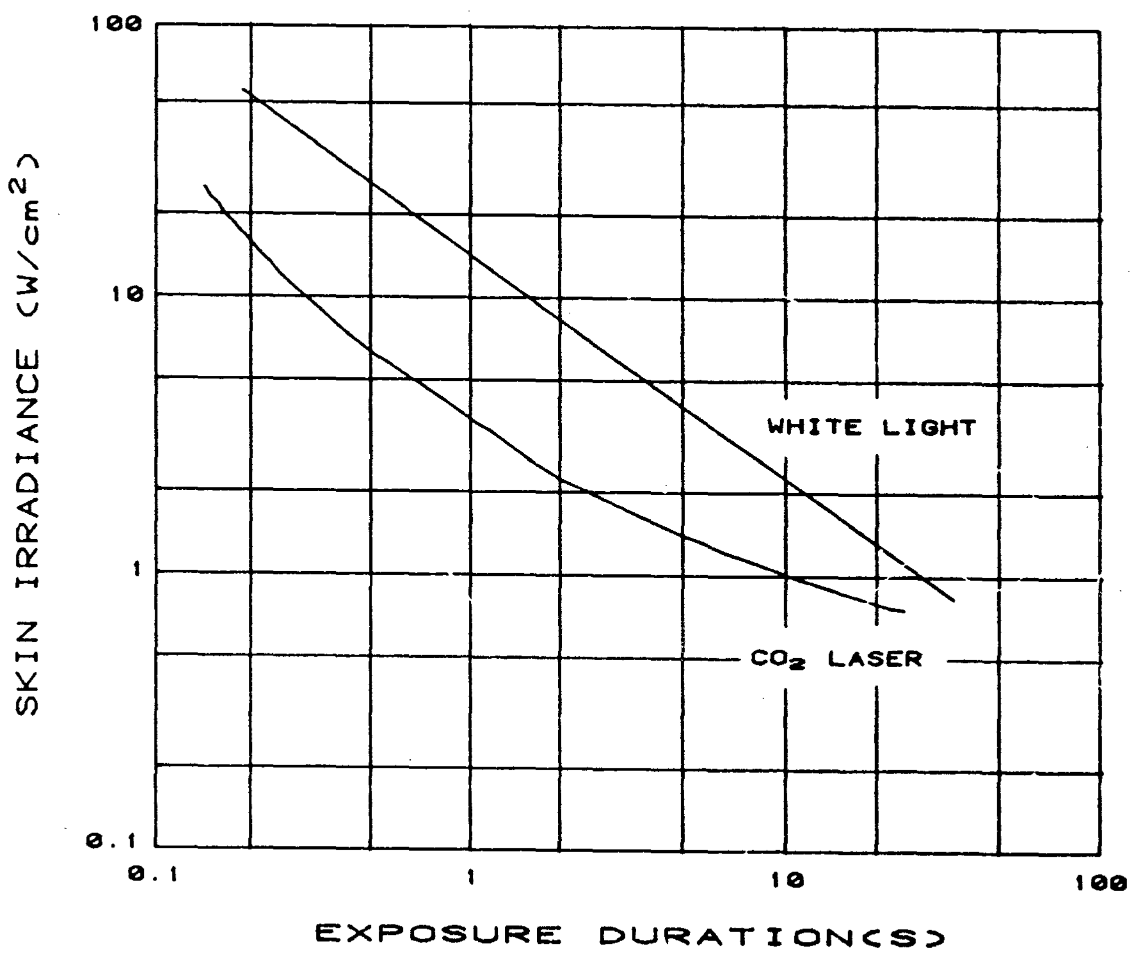


Figure 3. Irradiance Thresholds for First Degree Thermal Injury to Pig Skin from Infrared (CO_2) Laser and White Light (Modified after Sliney and Wolbarsht[32])

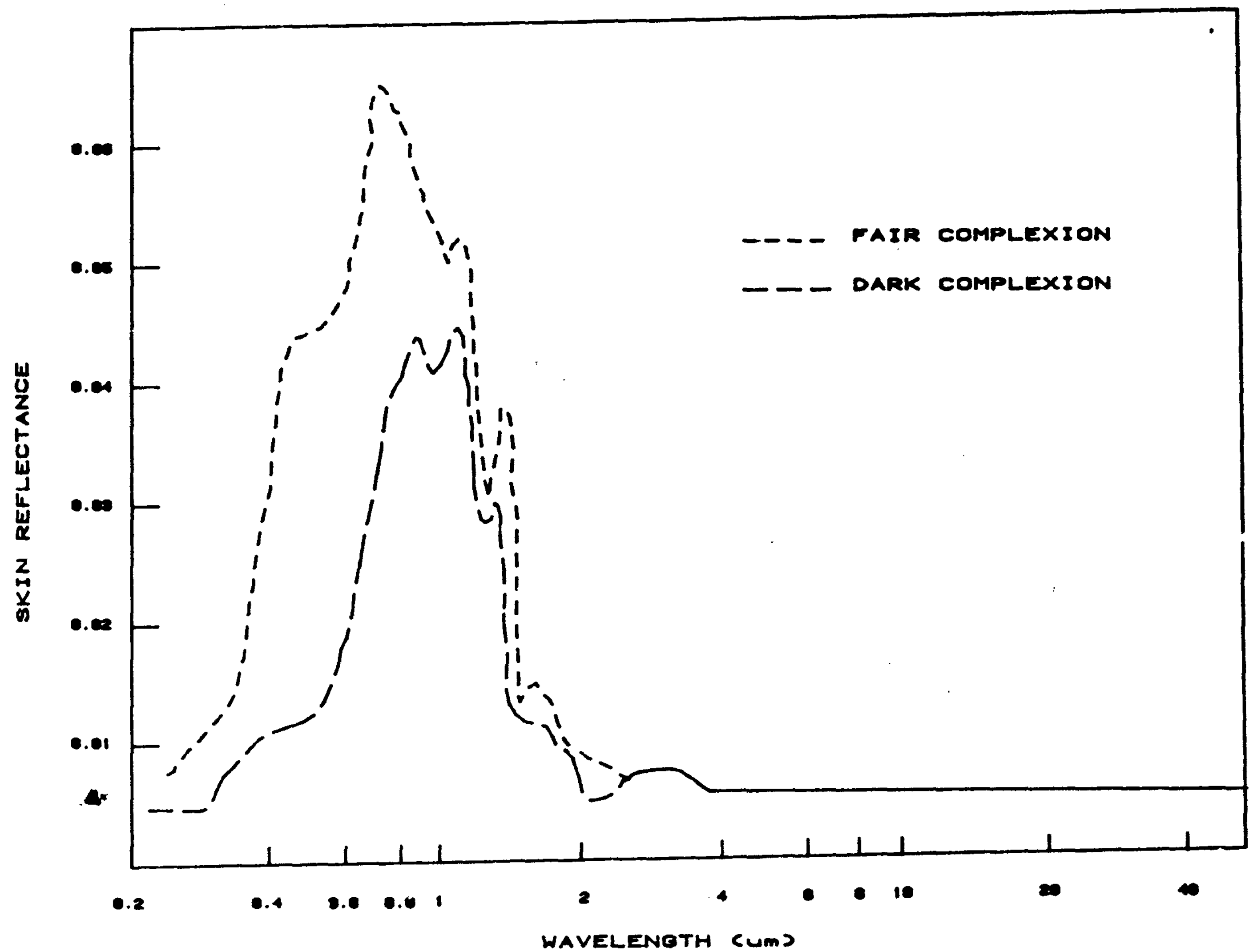


Figure 4. Reflectances of Human Skin to Optical Radiation (after Sliney and Wolbarsht[32])

What follows is a brief discussion after Skelly et al.[51] on responses of higher plants to visible and UV radiation. Other sources should be consulted for additional information.[52,53,54,55,56,57]

Visible Radiation - Visible radiation (400-700 nm), commonly referred to as photosynthetically active radiation (PAR) is essential for the formation of chlorophyll and is the source of energy to convert carbon dioxide, water, and minerals into carbohydrates and other plant nutrients. In addition, PAR also influences plant respiration and stomatal phototropic responses. Radiation in the red through near IR spectral regions influences vegetative growth and reproductive development in many species[55,58] (see Figure 5).

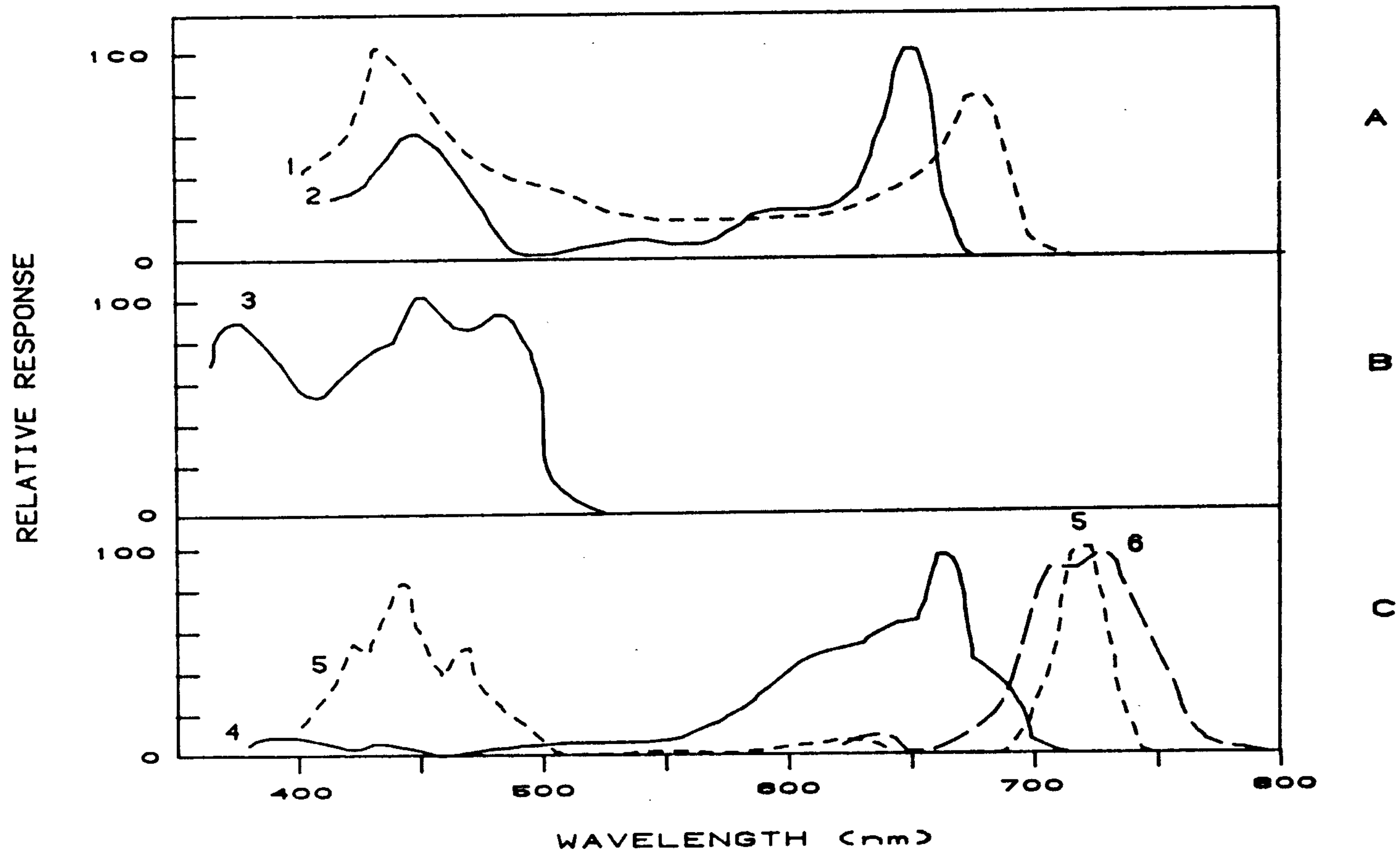
High irradiance from sunlight or other sources can injure photoreceptor systems in plants and cause photooxidation and photoinactivation of important cellular metabolites, pigments, and/or enzymes.[51,52]

Plant species vary widely in adaptations to PAR,* species in desert environments receiving up to several hundred times more solar radiation (quantum flux) than those at the floor of mature tropical forests. Shade plants, those adapted to growth in dim illumination, are able to use low irradiances much more efficiently than sun plants for photosynthesis and growth. They are incapable of high photosynthesis at high irradiances and are much more susceptible to irradiation stresses (e.g., drought injury, sun scald) at such levels.

Ultraviolet Radiation - Many cellular constituents absorb UV radiation in the 250-400 nm spectral region, which if great enough can result in several types of environmental stress. At northern latitudes, most UV radiation below about 290 nm is absorbed by the earth's atmosphere. This is fortunate because UV-C radiation is particularly damaging to nucleic acids (peak absorbtion at 265 nm) and has been shown to inhibit cell division and growth and to cause a number of pathologies to plant tissues.[51,54,59,60] UV absorption spectra of common plant chromophores are shown in Figure 6. Among the most common physiological disorders influenced by ambient UV radiation is sun scald, characterized by red or brown pigmentation of stems, leaves, and fruits, and sometimes by local necrosis and death of exposed tissues. Abnormal seedling growth was observed for several agriculturally important plant species exposed to UV-B radiation.[61] UV-B irradiation also elicited reciprocity-type abnormal responses (e.g., impairment of plant leaf photosynthesis) for up to 45 days following exposures.[51] Other disorders include various sunburn and sun bleach lesions of plant species ranging from red clover to Englemann Spruce.[51] The severity of these disorders will vary with a number of other environmental factors, including extreme temperatures, temperature fluctuations, and water stress.

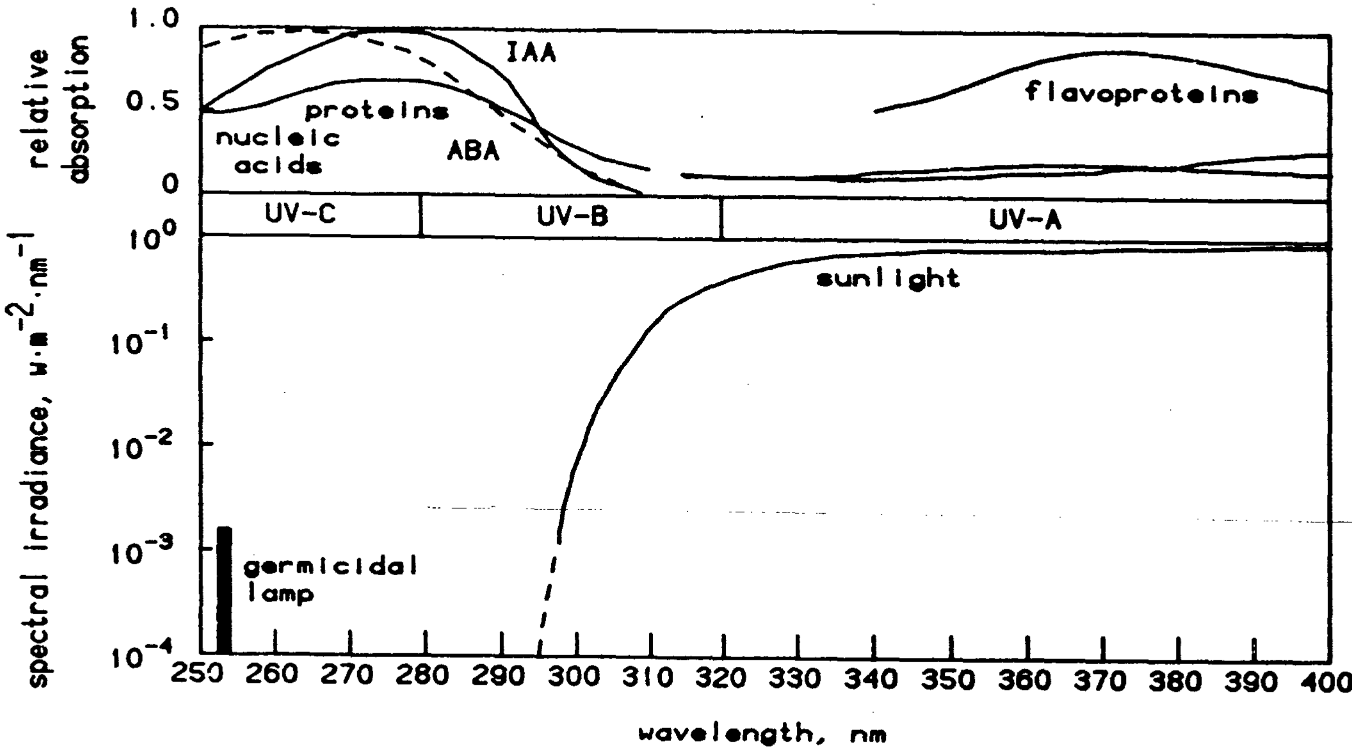
Plants have evolved different protective mechanisms to potentially harmful radiation. For example, most plants can reflect or else absorb much incident UV

*The solar constant, defined as the "flux of solar radiation across a unit area oriented normal to the solar beam at the mean sun-earth distance" equals ca 1.94 calories/cm^2/minute. Of this total, approximately one-half (52 percent) is at IR wavelengths longer than 700 nm, and 4 percent is at UV wavelengths, leaving ca 44 percent, 0.6 calories/cm^2/minute, for photo optic functions.[52]



A. Photosynthesis (1), chlorophyll synthesis (2).
B. Phototropism (3)
C. Photomorphogenetic induction (4),
photomorphogenetic high irradiance reaction (5).
reversion of photomorphogenetic induction (6),

Figure 5. Spectral Sensitivities of Some Photobiological Processes in Plants (after Fukshansky, in Smith[56])



Spectral irradiance at 30 cm from germicidal lamp and midday sunlight as would occur in summer at temperate latitudes. The absorbtion spectra of some common chromophores in plants are represented: ABA = abscisic acid; IAA = indoleacetic acid.

Figure 6. Ultraviolet Absorbances of Some Common Chromophores in Plants (after Caldwell[54])

radiation in epidermal tissues of leaves and stems, thus protecting more sensitive underlying tissues.[51,53] Other physiological responses help repair photochemical injury from intense UV-A and visible radiation. DNA photoreactivation has also been demonstrated in several plants and microorganisms[51,56]

To summarize, excesses or deficiencies of solar irradiance may stress plants by influencing rates of photosynthesis and other metabolic properties associated with plant growth and reproduction. Ecological impacts of such influences are difficult to interpret, especially at UV wavelengths where ambient exposures vary by up to 20 percent during normal 11-year solar cycles.

Potential effects of laser irradiation are virtually unknown for most plant photooptic responses. It is possible that coherent laser light may elicit physiological responses at lower exposures than incoherent light of the same wavelength (see 3.1.1.2) for similar relationships on animal vision). Much information is needed, however, regarding threshold responses (both beneficial and injurious) of plant tissues to laser light, particularly from high energy rapidly pulsed sources.

3.1.1.4 Other Effects.

Evidence of inhibitory effects of solar UV radiation on bacteria and other microorganisms is widespread.[51,62] These effects, which range from increased rates of mutation to decreased growth and viability, are caused chiefly by near UV radiation (300-380 nm), wavelengths below about 310 nm being most lethal.[51] Several photodynamic diseases of animals (i.e., skin cancers) have been attributed to long-term exposures to UV radiation;[63] relationships, if any, of UV laser light to these conditions again are unknown.

3.1.2 Propagation in the Atmosphere.

When a lasing source emits radiation in a vacuum, the irradiance at any distance from the source is calculated according to the inverse square law. However, when emitted through a gaseous medium like the earth's atmosphere, laser energy is modified by absorption, turbulence, and other phenomena. This section provides a brief description of the atmospheric factors most likely to influence transmission of laser radiation. Mathematical treatment of atmospheric transmittance of laser and other optical radiation is available from several sources[64,65,66] that should be consulted for further information.

3.1.2.1 Scattering and Absorbtion.

Scattering is defined as the deflection of light energy from the beam path and can result from laser interactions with air molecules (Rayleigh scattering), or with suspended particulates and aerosols like dust, smoke, or water droplets (Mie scattering). Absorption is defined as the transfer of energy from a beam to the molecules and particles in its path. Molecular absorption occurs only at certain wavelengths characteristic of the molecule's atomic structure. Molecular absorption and Raleigh scattering are influenced largely by atmospheric water vapor (H_2O), carbon dioxide (CO_2), and ozone (O_3) and tend to be greatest at UV and certain IR wavelengths. Particulate absorption and Mie scattering depend on the density and size distribution of atmospheric aerosols (typically from 0.1 to 1.0 micron in diameter), and are important determinants of laser propagation in the visible and near IR spectral region.

The net effect of scattering and absorption phenomena on transmission of laser light will vary with wavelength and intensity of the lasing source, pathlength, temperature, pressure, humidity, and composition of the local atmosphere. Figure 7 illustrates scattering losses (as percent attenuation per kilometer at sea level) for various atmospheric conditions. It is clear from this figure, which neglects absorption by water vapor and carbon dioxide, that particular scattering will limit transmission of short wavelengths much more effectively than long wavelengths. It has also been shown that scattering by water droplets (rain, fog, snow) is independent of wavelength in the visible to far IR region of the spectrum.[67] In Figure 8 scattering and absorption effects are included to show atmospheric transmission of light at visible and IR wavelengths under realistic conditions.* The various water and carbon dioxide absorption bands in this spectral region are denoted as areas of transmission (shaded) and attenuation (white). The absence of atmospheric attenuation of IR wavelengths at 3.3 to 4.4 m and 8.5 m and above suggests that laser emissions in these regions may be efficiently transmitted.

3.1.2.2 Turbulence.

The atmosphere is composed of moving masses of air, the result of nonuniform solar heating of ground, water, and air. The resulting atmospheric turbulences, or winds, can vary locally, but tend to be greatest from late afternoon to early evening when surface heat is most actively transferred to the atmosphere. Likewise, turbulence is often lowest at dawn when surface and air temperatures are near equilibrium.

Turbulence can modify the refractive index of air** by creating local air pockets of variable temperature and density. This, in turn, influences the degree and direction of bending (refraction) that can occur as a light beam passes through the air mass, the amount and direction of refraction depending on the wavelength of light, refractive index of the medium, and the angle at which the light strikes the medium. As a result, the distribution of energy within a laser beam can become less uniform and, therefore, less predictable.[17,32]

3.1.2.3 Reflections.

As light passes from one medium to another (e.g., air to water) photons are reflected and/or transmitted at media interfaces according to respective properties of the media, wavelength of the light beam, and the angle at which the incident light contacts the surface of the new medium. Other factors, including polarization of the incident radiation, will also influence transmission and reflection.[64]

Reflection phenomena are best discussed in terms of diffuse and specular surfaces. A diffuse, or opaque, surface is composed of randomly oriented irregular components much larger than incident light wavelengths. The resulting reflection occurs over a wide variety of angles and will dissipate the energy of the light source. In contrast, specular surfaces are mirror-like, being composed of imperfections much

*Data was gathered over a 300-m horizontal path near Chesapeake Bay, meterological conditions unspecified

**Refraction phenomena are responsible for the "shimmering" of images above hot terrain as heat rising from the ground disturbs the cooler air above it.

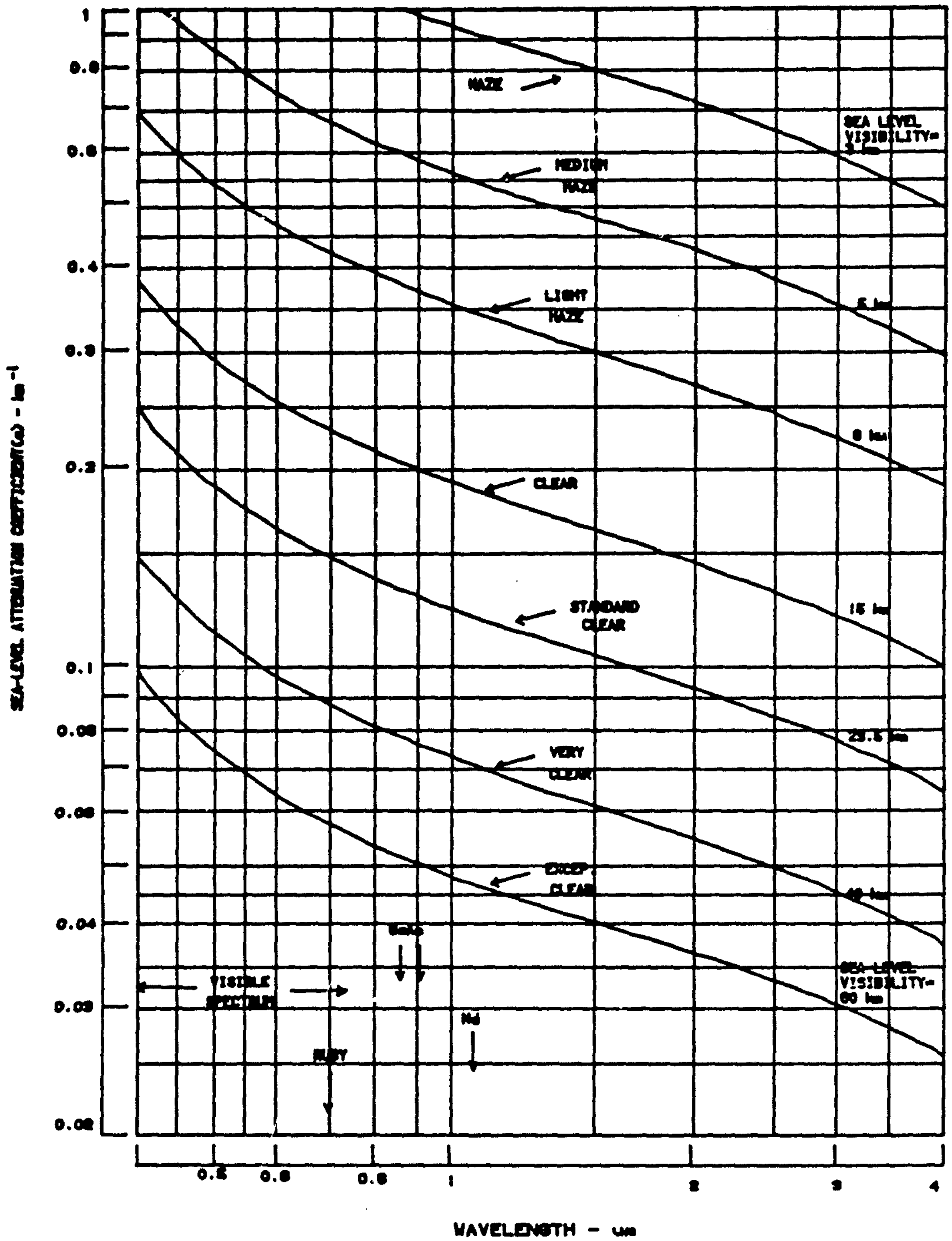


Figure 7. Attenuation of Optical Radiation at Sea Level for Different Atmospheric Conditions (Modified after RCA, Electro-optics Handbook[64])

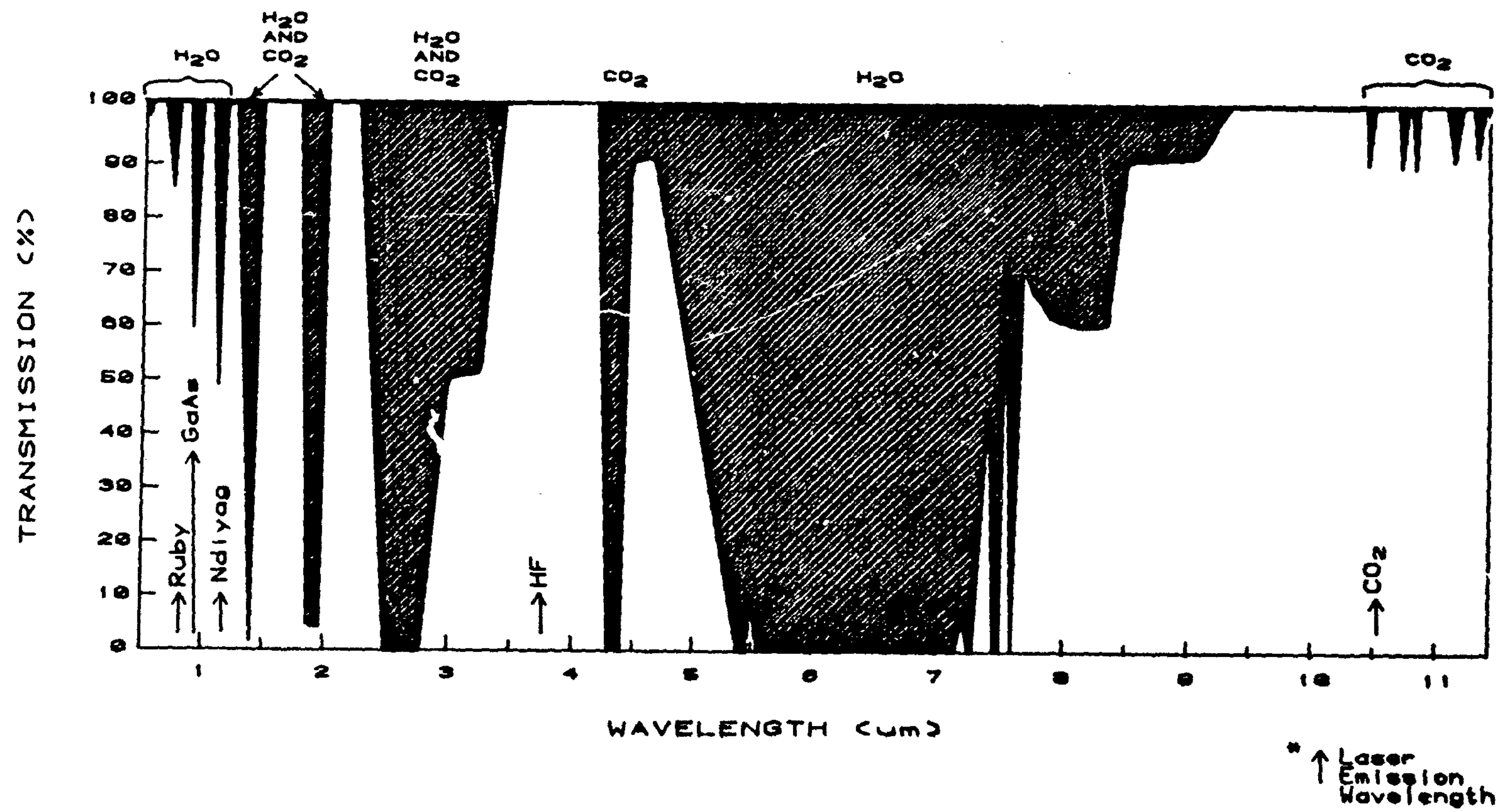


Figure 8. Atmospheric Transmission of Light by Wavelength (Modified after RCA, Electro-optics Handbook[64])

smaller than the wavelength of incident light (e.g., a polished surface). If the specular surface is flat, characteristics of incident and reflected beams are essentially identical. If curved, then reflected intensities will decrease according to the uniformity and curvature of the surface.[17,32]

Most surfaces in nature are diffuse and therefore unable to reflect incident coherent radiation efficiently. Some surfaces, however, may behave as specular or semispecular reflectors. For example, naturally specular surfaces generally have a small radius of curvature (e.g., water droplets, leaves) such that hazardous reflection levels exist only near the reflector. Still ponds and flat plate glass are likeliest to produce hazardous reflections at a distance. It should be noted that the potential for specular reflection increases with wavelength, so that for far IR laser wavelengths (e.g., a 10.6-m CO_2 laser), even dull metal and metal-like surfaces may be highly specular. As a general rule, laser irradiances or radiant exposures safe enough to view by diffuse reflection will not create hazardous reflections from water droplets and natural foliage at viewing distances greater than 1 meter.[17,32]

3.1.2.4 High Energy Effects.

At power levels below about 50 W/cm^2, thermal energy from laser light has little effect on its atmospheric environment.[64] At greater intensities, however, such energy may be transferred at high enough levels to alter this environment and its subsequent influence on laser propagation. High energy exchanges between laser beam and atmosphere are essentially nonlinear (i.e., energy losses occur at faster rates than power gains) and can result in thermal blooming and the ionization, or breakdown, of air molecules.

The term "thermal blooming" is used to describe self-induced thermal distortions of laser radiation. This occurs when air densities along the path of a laser beam are thermally altered enough to bend light from its directed course. This effect is proportional to the relative rate at which air transverses the beam (either as wind or by slewing of the beam), at least until relative air movements are great enough to prevent appreciable heat gain. Thermal blooming is more likely to occur with CW high energy lasers than with pulsed lasers, especially if the frequency of pulses is low enough to allow heated air to be removed from the beam path.

Ionization is the process of adding or removing electrons from an electrically neutral atom or molecule to form electrically charged ions. At high intensities (e.g., megawatts/cm^2) air molecules will ionize to create electric fields, or plasmas, strong enough to totally absorb laser energy.[64] Although it is possible to attain brief (nanosecond) air ionization intensities with certain pulsed lasers, the environmental importance of this phenomenon is unclear and may not differ substantially from atmospheric ionization caused by lightning.

3.2 Ancillary Factors.

In addition to biological effects of laser radiation, many lasing systems contain, or are associated with, other potential sources of environmental impact. The most important of these ancillary factors are discussed briefly below and more fully in other sources[17,32,68] that should be consulted for further information.

3.2.1 Chemical.

3.2.1.1 Fuels, Coolants, and Emissions.

Many chemical fuels, exhaust products, and coolants associated with lasing devices are potentially hazardous in the workplace or local environment, and exposure to these materials may be governed by local, state, or federal regulation (see 2.3 and 2.4). Laser systems requiring large storage and treatment facilties for lasing material and exhausts are especially subject to risks from exposure to hazardous chemicals. For example, operational requirements for current high energy HF or DF chemical lasers would result in atmospheric discharges of helium, oxides of nitrogen and sulfur, and several fluorinated compounds, including hydrogen (or deuterium) fluoride, a corrosive and environmentally toxic material.[69] Other fuels, reactants and emissions associated with HEL operations are listed in Table 4, along with possible airborne pollutants from laser impacts with target materials. Note that ozone (O_3), an important airborne photochemical oxidant (see 2.4.4), may result from HEL-produced atmospheric plasmas (see 3.1.2.4), although probably in amounts too low to be environmentally significant.

High energy laser facilities such as the HELSTF at White Sands Missile Range, are subject to federal and state regulations and permit requirements designed to insure environmentally acceptable methods for use and disposal of process effluents (see 2.4). Thus only in event of accidental discharges would potentially adverse local impacts be likely to occur. Potential impacts of this kind are addressed in appropriate site-specific environmental and safety documents.[11,12]

Many lasers are cooled during operation with materials ranging from water to liquid nitrogen or other cryogenic fluids.[32] When vented to the atmospehre, cryogenic fluids tend to displace oxygen and, in high enough concentrations, can act as an asphyxiant. Although a potential safety hazard near enclosed facilities, inert gases from exposed cryogenic fluid containers are unlikely to present significant environmental impacts as escaping gases would be rapidly diluted in the local atmosphere.

3.2.1.2 Dyes and Solvents.

Laser dyes are complex organic compounds that can be combined with appropriate solvents to produce lasing media capable of emitting at ultraviolet, visible, and IR wavelengths (see Figure 9).[70,71*] These fluorescent compounds are available commercially, and many can be classified by chemical structure into major groups such as the xanthenes (rhodamines and fluoresceines), polymethines (cyanines and carboncyanines), coumarins, and stilbenes.

Some of these dyes or closely related compounds are used commercially for other purposes.[70] Toxicological data on many compounds, however, are scarce, although

*Reference 70, a preprint of a paper given by J. A. Mosovsky at the American Industrial Hygiene Conference, 22-27 May 1983, Philadelphia, PA, is intended for formal publication and is used here with permission of the author. Requests for additional information should be addressed to the author or to the Technical Information Department, Lawrence Livermore National Laboratory, University of California, Livermore, California 94550.

Table 4. Potential Chemical Contaminants from Laser Operations

Substance	Worker Exposure[a] Limits (mg/m^3) TWA	STEL	Department of[b] Transportation Hazard Class	RCRA Waste[c] Category
Fuels, Reactants, Emissions[d]				
Bromine	0.7	2	Corrosive Material	—
Carbon dioxide (liquified)	9000	2700	Nonflammable Gas	--
Carbon monoxide	55	440	Flammable Gas	—
Chlorine	3	9	Nonflammable Gas	—
Deuterium (see hydrogen)				
Fluorine	2	4	Nonflammable Gas	Acute Hazardous Waste, P056
Helium	asphyxiant[e]		Nonflammable Gas	—
Hydrogen	asphyxiant[e]		Flammable Gas	—
Hydrogen fluoride	2.5	5	Corrosive Material	Toxic Waste U134
Nitrogen	asphyxiant[e]		Nonflammable Gas	
Nitrogen dioxide (liquified)	6	10	Poison A	Acute Hazardous Waste, P078
Sulfur dioxide	5	10	Nonflammable Gas	—
Solvents (Laser Dyes)[f]				
Chlorobenzene	350	—	Flammable Liquid	Toxic Waste U037
Chloroform	50[g]	225	ORM-A[h]	Toxic Waste U044
Cyclohexane	1050	1300	Flammable Liquid	Toxic Waste U056
Dichloromethane	360	1700	ORM-A[h]	—
Ethyl Alcohol	1900	—	Flammable Liquid	—
Ethylene Glycol	125 (vapor)	—	Combustible Liquid	—
Methyl Alcohol	260[i]	310[i]	Flammable Liquid	Toxic Waste U154
Tetrahydrofuran	590	735	Flammable Liquid	Toxic Waste U213
Toluene	375[i]	560[i]	Flammable Liquid	Toxic Waste U220
Triethylamine	40	60	Flammable Liquid	—

Table 4 (cont'd)

Substance	Worker Exposure[a] Limits (mg/m^3) TWA	STEL	Department of[b] Transportation Hazard Class	RCRA Waste[c] Category
Target Interactions[d]				
Asbestos	--[g]		N/A	N/A
Beryllium	0.002[g]		N/A	N/A
Cadmium Oxide (fume)	0.05		N/A	N/A
Chromium	0.5		N/A	N/A
Cobalt (dust & fume)	0.1		N/A	N/A
Copper (fume/dust)	0.2/1		N/A	N/A
Non Oxide (Fe_2O_3 fume)	5		N/A	N/A
Manganese (fume/dust)	1/5	3/-	N/A	N/A
Nickel	1	—	N/A	N/A
Ozone	0.2	0.6	N/A	N/A
Uranium (soluble & insoluble)	0.2	0.6	N/A	N/A
Vanadium (as V_2O_5 dust & fume)	0.005	—	N/A	N/A
Zinc Oxide (fume)	5	10	N/A	N/A

[a]Published by the American Conference of Government Industrial Hygienists[20] as safe to "nearly all workers" following repeated daily exposure. Categories include:
TWA (Time Weighted Average) - for normal 8-hour workday and 40-hour work week exposures.
STEL (Short Term Exposure Limit) - maximum concentration or ceiling not to be exceeded at any time during a 15-minute excursion period.

[b]See 49 CFR part 172.101.

[c]Resource Conservation and Recovery Act. See 40 CFR part 261.33

[d]Modified after Sliney and Wolbarsht, Ch. 27[32]

[e]Inert gas or vapor which limits availability of oxygen

[f]Modified after Mosovsky[70]

[g]Suspected carcinogen

[h]"Anesthetic, irritating, noxious, toxic or other similar property which can cause extreme annoyance or discomfort" (see 49 CFR 173.505)

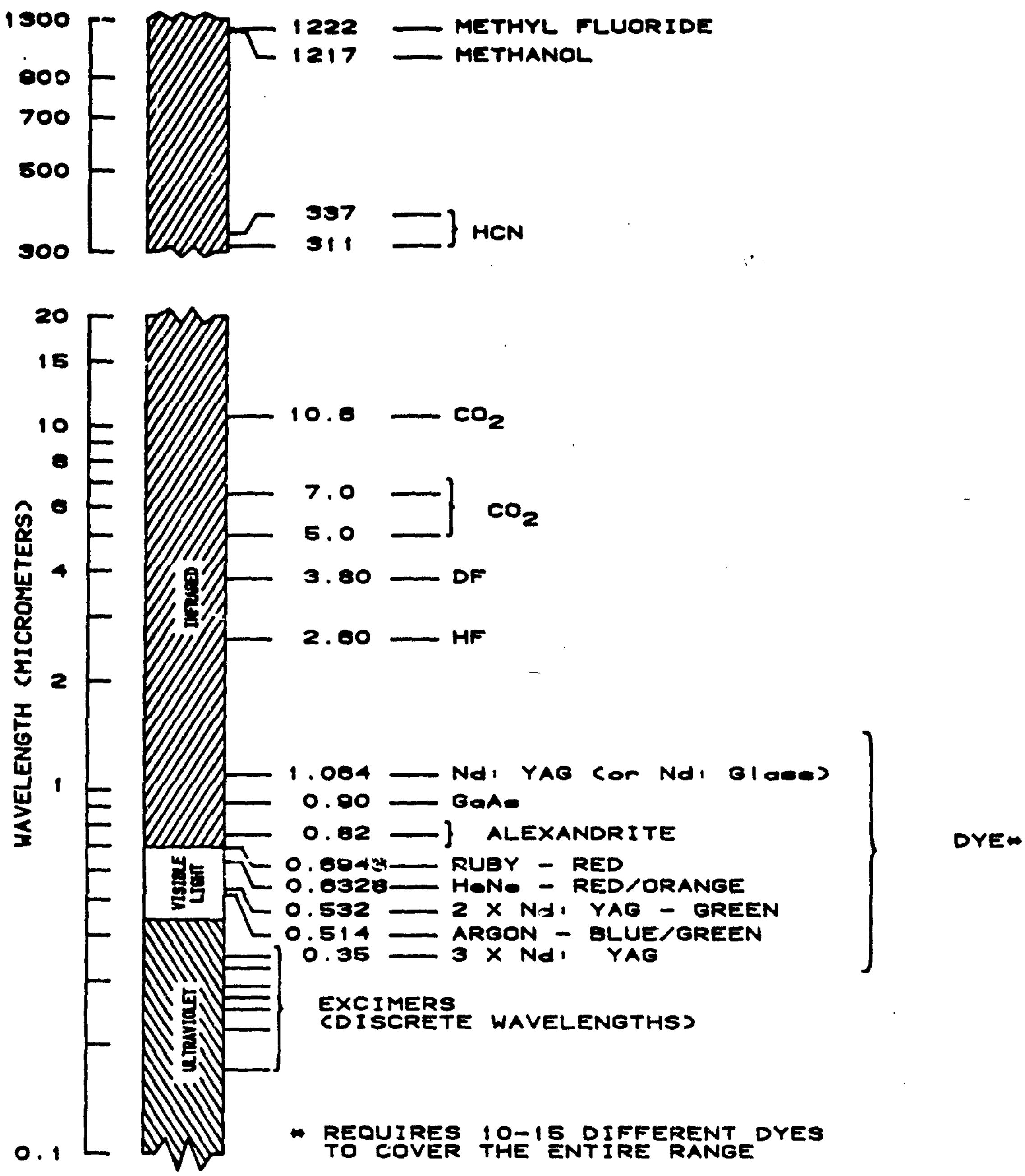


Figure 9. Operating Wavelengths of Some Commercial Lasers

available evidence suggests that some (e.g., cyanines, polymethines), taken orally, are potentially hazardous.[68,70,72] More important from the health and environmental perspective are the dye solvents, which typically comprise more than 99 percent of dye lasing media by weight, and which are commonly flammable and/or toxic by inhalation or percutaneous absorption (see Table 4).[68,72,73]

Risk of exposure to organic dyes and solvents is likely to be greatest during preparation of lasing media solutions. This operation should be confined indoors at facilities designed to handle such substances. Under field conditions, dye solutions in lasing devices would probably be protectively encased in relatively small quantities (less than 1 liter), and should not present significant environmental impacts if properly handled and disposed of by regulation (see 2.4.2).

3.2.2 Radiation.

Laser light is not capable of ionization (as are x and gamma rays) except at very high irradiances. However, x-rays can be generated from high-voltage (greater than 15 kv) power supply tubes and from certain electric discharge laser (EDL) systems. These radiation hazards are generally well understood and are limited to acceptable levels through proper monitoring and shielding procedures.[18,32]

3.2.3 Noise.

Excessive environmental noise (e.g., sound levels capable of disturbing sleep, speech, and/or of eliciting annoyance or other atypical behavioral or physiological responses) may result from certain laser operations. Hazardous sound levels can occur at source and target and, for certain HEL's, may result from superheated air during atmospheric propagation (thunder). Local impacts can be minimized through acoustical shielding, ear protection, and isolation of lasing operations from nonworker populations. Army standards for environmental noise are given in AR 40-5.[74] Additional information can be found in TB 501,[75] and ACGIH TLV's (pg 79).[20]

3.3 Summary of Environmental Risks.

Environmental risks from Army laser operations can be evaluated as potential impacts from downrange exposures to laser radiation and ancillary energy sources and chemical emissions from lasing devices and facilities. These criteria are summarized below with emphasis on relationships to major life cycle development phases of Army materiel.

3.3.1 Laser Radiation.

Local impacts from laser radiation cannot be estimated without knowledge of: the output (wavelength, power) of the lasing source, distance from lasing source to target, atmospheric conditions, and damage/injury thresholds for substances/organisms at risk of exposure. Although information on output parameters of Army lasers is often classified, typical output capabilities of many lasers can be estimated from published information on commercial laser devices. This has been done in Figure 9 and Table 5, which list (respectively) emission spectra and output characteristics of lasers of potential military utility. Given knowledge of these laser output levels, downrange human safety hazards can be estimated from standards for exposure and calculation aids (see Appendices C & D). Unfortunately these standards are progressively less useful for

Table 5. Output Characteristics of Typical Industrial Lasers[a]

Type	Wavelength µm	Repetition rate Hz	Pulse length µ sec	Peak output power in watts (w) or pulse energy (j)
Liquid (dye)				
Nd:YAG[b]	0.19 - 3	1 - 10	0.008	1.8×10^7 (j)
Eximer[b]	0.21 - 0.96	1 - 200	0.005 - 0.015	5×10^6 (j)
Coax - Flash[b]	0.46 - 0.75	0.6	1.8	5×10^6 (j)
Gas				
CO_2	10.6	0.016	2	36,000 (j)
CO_2	9.2 - 10.7	CW[c]	CW	150 - 15,000 (w)
CO	5 - 7	CW	CW	10 - 20 (w)
DCN	190/195	CW	CW	0.1 - 0.2 (w)
DF	3.8	CW	CW	10,000 (w)
HeNe	0.6328	CW	CW	0.01 (w)
	3.391	CW	CW	
HCN	311/337	CW	CW	0.01 - 1.0 (w)
HF	2.6 - 2.0	CW	CW	25 - 50 (w)
Methanol	37 - 1217	CW	CW	0.1 (w)
Methyl Fluoride	496 - 1222	CW	CW	0.025 (w)
Argon	0.45 - 0.53	3.8×10^6	10^{-2}	8×10^{-6} (j)
Solid State				
Nd:YAG	1.06	CW	CW	600 - 200,000 (w)
Alexandrite	0.73 - 0.78	1	0.1	1 (j)
Nd:YAG (x2)	1.06 (0.532)	5	14,000	80 (j)
Ruby	0.6943	0.016 - 0.25	2,000	150 - 400 (j)
Semiconductor				
GaAs	0.904	1,000	200	50 - 150 (w)

[a]Information compiled from a more extensive listing in the 1983 Laser Focus Buyers' Guide to indicate highest output capabilities of selected lasers.

[b]Pumping method

[c]Continuous wave

nonprimate mammals and other vertebrates and, until more data about laser effects on these animals are available, potential hazards should be evaluated against current standards for human exposure.

These exposure standards are of even less value for appraising hazards for plants and microorganisms. This is particularly true for laser radiation in the actinic UV spectrum (UV-B, C) which is potentially germicidal, mutagenic, and teratogenic to many plant species. Although visible and near IR wavelengths of some lasers are photoactive for certain vegetative functions, far IR radiation will probably cause thermal damage by mechanisms similar to those in animals (albeit at different depths and irradiances). However, in view of regenerative potentials of many plants, such damage may be short-lived and less threatening to overall survivability.

Much of the information presented above concerns mechanisms for potential injury to living tissues by laser light or other sources of optical radiation. Ultimately, however, such information must be used to estimate probabilities of injury under natural conditions and impacts, if any, that such injuries or deaths would have on the structure and stability of the lased environment. Answers of course will vary with each of the factors discussed above and with the structure of the environment at risk. Nevertheless, certain conclusions are possible and are summarized as follows:

> The greatest risk of injury to animal life is through ocular exposure to visible - near IR laser wavelengths. The chance of such exposure to any human or animal is slight and would require direct irradiance of ocular lenses probably less than 1 entimeter in diameter by a downrange laser beam generally much less than 100 centimeters in diameter. Plants, which unlike animals are unable to focus and intensify light through ocular lenses, would probably be unaffected by most low power visible laser radiation capable of ocular injury.
>
> High power lasers, i.e., those capable of producing fire or skin injuries, are also capable of injury to plant tissues as well. Unlike animal species, plants would be unable to move exposed areas which, if large enough, could result in death. Again, total downrange areas at risk of direct, or even specular, exposure to laser radiation normally would be very small.
>
> The greatest risks from high power laser irradiation would be from downrange fires, which could destroy local ecosystems indiscriminately. Chances of such fires would be greatest in relatively dry areas or following periods of prolonged heat, and it may be advisable to limit outdoor testing of HEL's under these conditions.
>
> Ultraviolet radiation is potentially most damaging to living systems because it is capable of altering genetic functions (mutagenesis) that theoretically could alter the local gene pools of a species. Ultraviolet radiation is efficiently absorbed by the earth's atmosphere at sea level and, therefore, is difficult to transmit for great distances at high power levels. Furthermore, although microorganisms would certainly be exposed and possibly affected by UV lasers, higher plants would probably be susceptible only if reproductive structures (e.g., flowers) were directly exposed. Chances of such exposures must certainly be slight and could only occur during seasons when such structures are being produced.

Most lasing devices are operated and aimed only with aid of an operator and, given that such individuals act responsibly, it is likely that procedural constraints of Army policies concerning laser range safety will limit potential downrange impacts from laser radiation to areas of military installations specifically established for such purposes. Additional precautions would possibly be required if laser ranges included or bordered habitats of threatened or endangered species, as defined by state and federal statutes.

3.3.2 Ancillary Hazards.

Viewed solely as a source of directed energy, laser radiation is virtually pollutionless. Indirect impacts are possible, however, from certain liquid and gaseous reactants and waste products of systems or facilities which produce laser energy. In most cases, quantities of potential pollutants are low (1 liter or less) and are packaged to insure little hazard to the user and surrounding environment. Potential pollutants (e.g., liquid dyes) could be found in larger quantities at storage facilities (e.g., depots), but only in case of a major accident (e.g., fire) would chances of environmental exposure increase significantly. Cleanup and disposal procedures in such cases are covered in respective facility/installation Hazardous Substance Spill Control and Contingency Plans.

Many research lasers (i.e., chemical, CO_2, GDL) require storage of common industrial gases and coolants (carbon dioxide, nitrogen, helium) which, if pressurized, may present an explosion hazard. Otherwise, they are essentially inert and of little environmental risk in the open air. By far the greatest source of environmental emissions from lasing systems are the high-energy research laser facilites, for instance, the HELSTF at White Sands Missile Range, New Mexico. As mentioned earlier, emissions from this and other such facilities are monitored and regulated to conform to federal and state regulatory requirements.

3.3.3 Life Cycle Events.

3.3.3.1 Research, Development and Training.

The greatest risks of environmental impact from Army laser programs will occur during outdoor developmental testing phases (e.g., operational and development testing) and during large-scale troop-training exercises. Such activities, if conducted within guidelines of AR 40-46 and respective MACOM range safety manuals, should result in environmental impacts much less significant than those from troop movements and other routine features of the training exercise.

Research involving HEL's is currently very limited, and long-range prospects for potential impacts of HEL's may be easier to determine once the military utility of potential designs are more thoroughly evaluated.

3.3.3.2 Production and Deployment.

Impacts for production of standard Army lasers are low, primarily because items are produced on contract by commerical sources not located on military installations. These industrial sources are subject to environmental regulations of respective local, state, and federal jurisdictions. Affected environments for proposed storage of laser devices and ancillary materials will be addressed as required in appropriate environmental documents.

3.3.3.3 Demilitarization and Disposal.

Potential impacts for demilitarization and disposal procedures of laser systems will vary with the design and type of lasing system, but these procedures should not pose significant environmental problems in any event. Typically, metal and other structural components would be incinerated and sold as scrap. Chemicals (e.g., coolants, dyes) would be drained and incinerated or otherwise appropriately disposed of; containerized gases and electrical components would be salvaged and/or recycled. The affected environments of proposed demilitarization and disposal facilities would be addressed and documented as required by Army regulation.[2]

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APPENDIX A

Background Information: Theory and Operation of Lasers

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1. GENERAL INFORMATION

The word "laser," an acronym for light amplification by stimulated emission of radiation, will be applied in this appendix to devices with output wavelengths of approximately 200 nm (0.2 μm) to 1000 μm (1 mm).* What follows is a brief discussion of the principles of laser light and lasing devices. Much of this material has been modified after TB 279,** which should be consulted for additional information.

1.1 Nature of Light.

As commonly used the word "light" refers to that portion of the electromagnetic spectrum which produces a visual effect. It was first shown by James Clerk Maxwell in 1873 that light is electromagnetic radiation that propagates at approximately 3×10^8 meters per second. Albert Einstein later predicted that the velocity of light in a vacuum is constant throughout the universe and is the ultimate speed at which energy may be transmitted. Quantum mechanics, the branch of science dealing with atomic and subatomic particles, describes the smallest indivisible quantity of radiant energy as one photon. The amount of energy, represented by one photon, Qq, is determined by the frequency ν (NU), and Plank's constant, h.

$$Qq = h\nu$$

The frequency, ν, and wavelength, λ (lambda), of light are related by the velocity of light, c, so that knowing one, the other may be determined by use of the relationship.

$$c = \nu\lambda$$

Man has made use of almost the entire electromagnetic spectrum from zero Hertz (cycles per second), i.e., direct current from storage batteries, to 10^{24} Hertz, i.e., the very hard x-rays for nondestructive inspection of metal parts. Figure A-1 shows the electromagnetic frequency spectrum and some of its uses and properties.

Electromagnetic radiation is emitted whenever a charged particle, (e.g., an electron) gives up energy into an electric field. This happens whenever an electron drops from a higher to lower energy state in a molecule, atom, or ion. In ordinary light sources, electron transitions from higher to lower energy states occur randomly and one photon has no correlation with another. Electrons can be raised to higher energy levels or become "excited" in many ways: (a) by heating, as in the filament of an incandescent-lamp; (b) by collisions with other electrons, as in a fluorescent lamp or television picture tube; (c) by absorbing energy from photons, as in luminescent paint on a watch dial; and (d) by chemical reactions, as in a flame. Electron energy levels are also influenced by the vibrational and rotational motion of a molecule.

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*nm=nanometers (10^{-9} meters); μm=micrometers (10^{-6} meters)

**Department of the Army Technical Bulletin. TB Med 279. Control of Hazards to Health from Laser Radiation. 30 May 1975.

Light from any source can be described in terms of line* or thermal emissions. Line emission occurs at a single wavelength, or color, of light. It is produced by the decay of an atom from some high energy state to a lower energy state. Among examples of line emitters are the sodium and mercury vapor lamps for highway lighting. Thermal, or broadband, emission is responsible for the light of incandescent light bulbs. Thermal emissions are composed of a continuous spectrum of colors and appear white to the human eye. The incandescent light bulb is a common source of thermal emissions.

1.2 Laser Light.

The laser is a type of line emitter which differs in two principal ways from other line emitters. First, the laser must be raised or "pumped" to an excited state in such a way that the upper energy state has a higher population density than the lower energy state. This "population inversion" results in an excited system with a large number of potential atomic transitions to be discharged. Each transition will result in the release of a photon of energy and the drop of an atom to a lower energy level. Secondly, these emissions are not spontaneous, as the electron transitions that produce laser photons must be stimulated by other identical photons (simulated emission). The overall effect of these differences is that the laser can store a very large quantity of energy that can be released quickly when appropriately stimulated.

Laser light has four typical properties which distinguish it from other types of light. A brief explanation of these characteristics is provided below:

Monochromicity. Light from incandescent sources is a mixture of many wavelengths or colors. This can be verified by placing a prism in the path of the beam. White light, (e.g., sunlight) or light from an incandecent bulb can be separated into various colors (red, orange, yellow, green, blue, and violet) by a prism. With monochromatic light, however, only one color exists and separation cannot occur.

Laser light is propagated essentially at a single wavelength (line emission), although minor variances in emission wavelengths are known to occur. For example, many lasers emit at two or more finite wavelengths simultaneously. For all practical purposes, however, laser light may be considered monochromatic.

Directionality. Normal light diverges rapidly from a source. Laser light, on the other hand, diverges very little and can be focused into a very narrow beam or cone. This characteristic makes lasers valuable in communications transmitters and, for precision measurements, pointing, and tracking.

Intensity. Closely related to directionality is the brightness or intensity of laser light. The intensity of a laser beam is defined by the amount of power radiated by the laser within its narrow cone of divergence, and can be described in several terms, including those of radiant intensity, radiance, irradiance, or radiant exposure (see Appendix B).

*The word "line" refers to the manner in which single wavelength (or monochromatic) light is displayed in a commonly used measuring instrument, the spectrograph.

The intensity of a laser beam can be greatly enhanced by focusing the beam to the smallest possible spot size. The diameter of the spot size for a focused laser beam is directly proportional to the range and wavelength and inversely proportional to the diameter of the aperture (the output lens or mirror).

Ideally, the cross section of a laser beam is circular, the light intensity greatest at the center and decreasing uniformly towards the perimeter (Gaussian distribution). This pattern is difficult to achieve for many types of lasers and requires accurate mirror alignments. As a consequence, certain wave pattern aberrations can be formed across the direction of beam propagation. These electromagnetic field variations are called transverse electromagnetic modes (TEM) and are caused by imperfections within lasing cavities, mirrors, and lenses, and/or by atmospheric turbulence (scintillations). One consequence of TEM's is the production of hot spots, or local irradiance variations of up to two orders of magnitude within the propagating beam.

Coherence. Coherent light is produced when light waves of the same wavelength are in phase with one another. The coherent property of laser light is closely related to the other properties discussed above. Thus, coherent light is monochromatic and highly directional. A coherent beam has extremely low divergence and can be focused at the source of the light rather then at the target. Because it can be concentrated within a narrow light cone, the brightness, or radiant intensity, is very great.

2. THE LASING PROCESS

The laser is an optical amplifier, analogous to an electronic amplifier in that a small light signal is amplified to produce a large output light signal. The laser has three basic components: a lasing medium, a pumping system (energy source), and a resonant optical cavity. Lenses, mirrors, shutters and other accessories may be added to the system to obtain more power, shorter pulses, or special beam shapes, but only three basic components are necessary for laser action.

2.1 Lasing Medium.

A lasing medium must have at least one excited state (metastable state) where electrons can be trapped and not immediately and spontaneously dropped to lower states. Electrons may remain in these metastable states for a few microseconds to several milliseconds. When the medium is exposed to the appropriate pumping energy, the excited electrons are trapped in these metastable states long enough for a population inversion to occur. Although laser action is possible with only two energy levels, most such actions involve four or more levels. Lasing media include solid state, gas, liquid (dye), semiconductor (diode), and free electron systems.

2.1.1 Solid state.

Solid-state lasers employ doped glass or solid crystals as the lasing medium. Examples include ruby (crystalline aluminum oxide) doped with chromium ions, yttrium aluminum garnet (YAG), doped with niodynium ion (Nd^{3+}) and erbium doped glass. Solid-state lasers normally emit in the near IR spectrum but can be modified to emit at shorter wavelengths. For example, the primary 1.06-μm (IR) output wavelength of a (Nd: YAG) laser can be halved to 0.53 μm (green) by doubling the frequency (see appendix B).

Wavelengths can be further shortened, but at the cost of significant reductions of output energy (doubling efficiencies are currently less than 40 percent).

2.1.2 Gas.

Gas lasers employ pure gas or gas mixtures as the lasing medium. An important example is the carbon dioxide (CO_2) laser, actually a mixture of CO_2, nitrogen (N) and helium (He) gases, which is capable of high power levels at relatively high efficiencies. Another common laser employs a mixture of He and neon (Ne) gases.

Excimer lasers are gas lasers composed of mixtures of rare gases and halogens, the halogen being any of the five chemically related nonmetallic elements (fluorine, chlorine, bromine, iodine, and astatine). The word "dimer" is used to describe a compound formed by the union of two similar molecuies. The term "excimer" is a contraction of the phrase "excited-dimer" and refers to a molecule which is chemically stable only in its excited state. Common excimer laser molecules include krypton fluoride (KrF), xenon fluoride (XeF), xenon chloride (XeCl), and mercury chloride (HgCl). Gas lasers emit primarily at IR wavelengths, CO_2 laser emissions occurring at 10.6 µm.

2.1.3 Liquid Dye.

Dye lasers employ active material in a liquid solution or suspension. Examples include complex organic dyes like rhodamine 6G and disodium fluorescein in alcohol or other suitable solutions. An important property of these materials is that the wavelength, or color of the laser, can be varied or tuned. Dye lasers can emit laser light at UV, IR, and visible wavelengths.

2.1.4 Semiconductor.

Semiconductor lasers employ transistor materials as the laser medium. As its name implies, a semiconductor is any material whose electrical conductivity is greater than that of an insulator (e.g., glass, plastic), but less than a good conductor like silver or copper. One such compound is gallium arsenide (GaAs) which can be modified into other lasing semiconductor alloys. Laser diodes commonly have low energy emissions at IR wavelengths (0.9 - 1.5 microns), although emissions at shorter (visible) wavelengths are possible with some materials.

2.1.5 Free Electron.

Free electron lasers differ from the other active laser media discussed above in that laser energy is supplied by unbound (free) electrons rather than from electrons bound to atoms or molecules. Although still experimental, electron lasers are potentially efficient, tunable, and powerful sources of coherent radiation.

2.2 Pumping System.

Lasers employ pumping systems to increase the number of electrons trapped in a metastable energy level. When electrons in the metastable energy level exceed those in the lower level, a population inversion exists and laser action is possible. Several common pumping systems are discussed below.

2.2.1 Optical.

Optical pumping normally occurs with solid-state or liquid-dye lasers. In each case lasing molecules are excited by interactions with photons from an external light source (e.g. xenon flash tube, ruby laser). Lamp-pumped lasers are often more efficient than laser-pumped lasers and result in comparatively longer laser pulses (microseconds to milliseconds), unless modified to produce pulses of picosecond to nanosecond durations. Optical pumping is currently effective for low power lasers of less than about 200-w average power output. Although methods exist to produce much higher power outputs, significant cooling requirements and other problems serve to limit the utility of such systems.

2.2.2 Electron.

In an electron pumping scheme, electrons are created by exposing the lasing medium to an electric current or to a plasma discharge. Plasma discharges can be created by passing high voltages across gas-filled tubes. The result is an ionized gas which supplies necessary electrons to the lasing medium. The electron beam, or electric discharge laser uses an electron gun similar to that of a television picture tube to inject electrons directly into the laser medium (usually a gas). Another type of electrical pumping causes electric voltage to vary at high frequency to create electric field waves along the laser gas (i.e., CO_2 lasers). Electron pumping is used with high and low power lasers in either CW or pulsed modes.

2.2.3 Chemical.

As the name implies, chemical pumps require chemical reactions to provide energy to lasing media. The most common chemical pumps involve reactions between hydrogen (H_2) or deuteurium (D_2) and fluorine (F_2) gases, which, when mixed, will react violently to produce the appropriate fluoride (HF or DF). The energy states of these reactant molecules are suitable as lasing sources for only an instant (about a millisecond), so that the gases must be mixed in supersonic flow through nozzles to extend lasing times as long as possible. Both HF and DF reactions are able to produce high energy laser outputs in the IR spectrum, the HF laser emitting at 2.7 μm, the DF at 3.8 μm.

2.2.4 Gas Dynamic.

It is also possible to produce high energy lasers by means of gas dynamic pumping, a system in which jet fuel is burned in a combustor to yield CO_2 gas at very high temperatures and pressures. Transitory (millisecond) lasing conditions are created by accelerating CO_2 molecules to supersonic velocities at low pressures, thereby lowering temperatures suddenly enough to create requisite population inversions. As with high energy chemical laser reactions, gas dynamic laser output can be prolonged through control of flow rates and nozzle designs.

2.2.5 Radio Frequency.

Long wave (radio frequency) electromagnetic radiation is capable of pumping numerous lasing gases (HF, DF, CO_2, N_2O and several rare gases), each lasing at different wavelengths. Radio frequency pumped lasers can operate at either continuous or pulsed modes at electrical efficiencies of up to 12 percent.

3. OPTICAL CAVITY.

A resonant optical cavity is formed by placing a mirror at each end of the laser material so that a beam of light may be reflected from one mirror to the other, passing back and forth through the laser material. Lasers are constructed in this way so that the beam passes through the material many times and is amplified each time. One of the mirrors is only partially reflecting and permits part of the beam to be transmitted out of the cavity.

In the case of high energy lasers, partially reflecting mirrors would absorb too much energy and be destroyed. Consequently, high energy lasers extract power either through a hole in the center of one mirror or around the outside edge of one mirror. The latter is more common. Other special configurations of mirrors with high reflectivity are also used.

4. MODES OF OPERATION.

The different modes of operation of a laser are distinguished by the rate at which energy is delivered. In general, lasers operating in the normal pulse mode have pulse durations of a few microseconds to a few milliseconds. This mode is referred to as "long pulse" or "pulsed" operation.

The quality of the optical cavity of a laser can be changed by placing a shutter between the mirrors. This enables the beam to be turned on and off rapidly and normally creates pulses in the nanosecond to a microsecond range. This mode of operation is normally called Q-switched, although it is sometimes referred to as Q-spoiled or giant pulse. (The "Q" refers to the resonant quality of the optical cavity.) A laser operating in the Q-switched mode delivers less energy than the same laser operating in the normal pulse mode, but the energy is delivered in a much shorter time period. Thus, Q-switched lasers are capable of delivering very high peak powers of several megawatts or even gigawatts. Most military lasers are Q-switched with a pulse duration of 10 to 30 nsec and are used in target acquisition and fire control.

When the phases of different frequency modes are synchronized, i.e., "locked together," the different modes will interfere with one another to generate a beat effect. The result will be a laser output that is observed as regularly spaced pulsations. Lasers operating in this fashion, mode-locked, usually produce trains of pulses, each having a duration of a few picoseconds to a few nanoseconds. A mode-locked laser can deliver higher peak powers than the same laser operating in the Q-switched mode.

Some lasers are able to operate continuously. This mode of operation is called continuous wave or CW. The peak power is equal to the average power output; that is, the beam irradiance is constant with time.

Pulsed lasers can be operated to produce repetitive pulses. The pulse repetition frequency of a laser is the number of pulses produced by the laser in a given time. Lasers are now available with pulse repetition frequencies from hundreds to several thousand pulses per second. Enormous variation exists for the number of possible pulse widths and pulse repetition frequencies. Therefore, the specification of such pulse characteristics is extremely important in any evaluation of the interaction of laser radiation with biological systems.

APPENDIX B

Glossary of Laser Terminology and Acronyms

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Absorption: the transfer of energy from one medium to another. When a laser beam is transmitted through the atmosphere, the beam will lose some of its energy to the atmosphere by absorption.

Absorption depth: the depth in a material that electromagnetic radiation will reach when part or all of the radiated energy is absorbed. The absorption depth depends on material properties and radiated wavelengths.

Accommodation: the ability of the eye to change its focus for different object distances

ACGIH: American Conference of Government Industrial Hygienists

Actinic: ultraviolet radiation (UV B&C) capable of producing chemical effects

Active medium: the atoms or molecules that provide for laser oscillation, also called laser medium, lasing medium, or active material

AEHA: US Army Environmental Hygiene Agency

Angstrom (abbreviated A): a unit of measure of wavelength equal to 10^{-10} meter, 0.1 nanometer, or 10^{-4} micrometer. This term is no longer widely used.

AQCR: Air Quality Control Region

ASL: Atmospheric Sciences Laboratory

Athermal effect: any effect due to radiation absorption other than the production of heat

Atmospheric degradation: the reduction of laser beam energy propagation through airborne particles or molecules by absorption, scattering or refraction. Effects vary with laser wavelength, particle size, density, and composition (e.g., dusts, smokes, aerosols, gases, fumes).

Attenuation: the decrease in the intensity of any optical beam as it passes through an absorbing and/or scattering medium

Average power: the power available averaged over the modulation cycle the power actually available to do work. In pulsed systems, average power is the peak power multiplied by the duty cycle. In continuous wave systems, average power is considered to be the rated power output.

Bandwidth: the frequency range over which a device or sensor system operates. The term is sometimes used for the special linewidth of an optical source (see linewidth).

Beam controller: a system of movable mirrors for pointing and focusing a laser beam

Beam diameter: the diameter or a cross section of a laser beam for which the power-per-unit-area is $^1/_e$ (=37%) of the peak power. Beam diameter is therefore less than the actual or apparent diameter.

Beam divergence: the increase in beam diameter with distance from the laser's exit aperture. The angle of beam spread is measured in milliradians (milliradian = 3.4 minutes-of-arc or approximately 1 mil). For small angles where the cord is approximately equal to the arc, the increase in the diameter of the beam is numerically

equal to 1/1000 of the range in meters multiplied by the number of milliradians of beam divergence. For example, at a range of 1000 meters a beam divergence of 2 milliradians would give a beam diameter 2 meters wider than the emergent beam diameter.

Beam splitter: an optical device using controlled reflection to produce two beams from a single incident beam

Blooming: the defocusing or bending of a laser beam as it passes through laser heated air

Brightness: see radiant intensity.

CAA: Clean Air Act

CERCLA: Comprehensive Environmental Response, Compensation, and Liability Act of 1980

Chemical laser (CL): a laser which uses a chemical reaction to produce the energy for the lasing action. The term usually refers to a deuterium fluoride or hydrogen fluoride laser.

CL: Chemical Laser

Coherent light: light which has a single frequency and a uniform wavefront. Often used for monochromatic light of a single wavelength

Collimated beam: an ideal, parallel beam of radiation. Laser beams in the atmosphere are focused or slightly divergent. A collimator is an optical device to convert a diverging or converging beam of light into a collimated or parallel beam.

Continuous wave (CW): an uninterrupted wave radiation. In contrast to an interrupted or pulse wave, CW lasers emit for a period of 0.25 sec or more.

CO_2 laser: an electric laser which uses carbon dioxide, nitrogen, and helium as the lasing medium. Wavelength: 10.6 μm (far IR).

Crystal laser: see solid state laser.

DA: Department of the Army

DARCOM: US Army Materiel Development and Readiness Command

Decibel (dB): a unit used to express the relative difference in power between acoustic or electric signals, equal to 10 times the common logarithum of the ratio of the two levels.

Designator: device which illuminates a threat with coded laser light detectable by sensors on conventional munitions for guidance to the target

Deuterium fluoride (DF) laser: a type of chemical laser. DF wavelength is 3.8 μm (mid-IR).

Diffraction: the bending or spreading of light waves caused by the interference of adjacent waves. Commonly associated with the spreading of light after it passes through a small hole, slit, or aperture.

Diffuse reflection: the reflection which occurs when different parts of a beam incident on a surface are reflected over a wide range of angles

Diode laser: a laser in which the active material is a semiconductor

Divergence: see beam divergence.

DOD: Department of Defense

DOE: Department of Energy

Duty cycle: a measure of lasing time for a repetitively pulsed laser. Expressed as the ratio of pulse duration to pulse repetition time (PRT). A duty cycle of 0.1 means that the laser is emitting for 10% of the duration of a pulse.

Dye laser: a laser in which the active material is an organic dye, generally in solution, with the liquid either flowing or encapsulated within a cell. Also called organic-dye, tunable-dye or liquid laser.

Electric discharge laser (EDL): a laser which uses electric power to induce the lasing action.

Electromagnetic radiation: the propagation of varying electric and magnetic fields through space at the speed of light

Emergent beam diameter: the diameter of a laser beam at the exit aperture of the system, usually measured in centimeters (cm)

Energy: the capacity for doing work. Energy is commonly used to characterize the output from pulsed lasers, and it is generally measured in joules (j).

EPA: Environmental Protection Agency

Excimer laser: a laser in which the active material is an excimer, a molecule chemically unstable except in its excited state. Common excimer lasers are KrF and XeF.

Exempted Military Laser: a laser that has been given an exemption from the Federal Performance Standard for Light-Emitting Products, 21 CFR 1040.10 and 1040.11, in accordance with a blanket exemption given to DOD by the Food and Drug Administration, and granted by the developing command or program manager in accordance with the provisions of AR 385-9. The use and disposal of exempted military lasers are strictly controlled.

Extended source: an extended source of radiation which can be resolved into a geometrical image (in contrast with a point source of radiation, which cannot be so resolved)

FDA: Food and Drug Administration

Field-of-regard: the area or angle a laser weapon can cover without motion of the carrier

Flashblindness: a temporary degradation in visual acuity resulting from irradiation of the eye(s) by a brief but intense visible light. The effects may last from a few seconds to a few minutes.

FLIR: Forward looking infrared

Fluence: a measure of radiant energy per unit area measured in joules/cm^2

Flux: a measure of radiant power per unit measured in watts/cm^2

Free-electron laser (FEL): a laser that differs from all others in that the optical energy comes from unbound (free) electrons rather than from electrons which are bound to an atom or molecule. Although still experimental, these lasers offer potential to be efficient, tunable, and very powerful sources of coherent radiation.

Frequency: the rate of vibration of an electromagnetic wave. Frequency is inversely proportional to the wavelength.

Frequency doubler: a crystal or other mechanism which doubles the frequency (or halves the wavelength) of incident laser radiation (e.g., changes 1.06 μm to 0.53 μm). A doubling efficiency of 35% is common for doubling 1.06 μm at the present state-of-the-art.

FWPCA: Federal Water Pollution Control Act of 1972.

Gas dynamic laser (GDL): a laser which uses expanding hot gas, usually from a combustor, through supersonic nozzles to produce the lasing action

Gas laser: a type of laser in which the lasting action takes place in a gas medium. Can be CW or pulsed operating mode

Glass laser: see diode laser.

Green laser: a laser which operates in the visible green band, typically a frequency doubled Nd: YAG laser.

HEL: high energy laser

HELSTF: High Energy Laser System Test Facility, located at White Sands Missile Range, New Mexico.

Hemorrhagic lesion: a lesion that is characterized by severe retinal burns with bleeding and immediate to permanent loss of view

Hertz (Hz): a measure of frequency (1 cycle per second). Hertz also indicates how many pulses per second a laser can produce.

High energy laser (HEL): a laser whose energy level enables it to burn through surface material or cause out-of-band damage to sensor systems. HEL is sometimes defined as any laser with an average power exceeding 20 kilowatts, or a single pulse energy of 30 kilojoules or more.

Infrared radiation (IR): electromagnetic radiation with wavelengths which lie within the range of 0.7 to 1000 μm (1 mm). This region is often broken up into near-IR, (0.7 μm to 1.4 μm), mid-IR (1.4 to 10 μm), and far-IR (10 μm to 1 mm).

Intensity: radiant exposure or irradiance

Intrabeam viewing: viewing the laser source from within the beam. The beam may either be direct or specularly reflected.

Ion: When an electrically neutral atom acquires or loses one or more electrons, the resulting charged species is called an ion. In the first case it becomes a negative ion, and in the second case a positive ion.

Irradiance: the radiant flux (radiant power) incident upon a given surface, measured in watts per square centimeter

Jitter: the erratic, transverse movement of a laser beam during transmission caused by turbulence and platform motion. A measure of the ability to hold a laser spot steady usually expressed in microradians.

Joule (J): a unit of energy. A joule is equal to 1 watt-second, or approximately 0.001 BTUs (British Thermal Units).

Joule/cm^2: a unit of radiant exposure used in measuring the amount of energy per unit area of absorbing surface, or per unit area of laser beam. Normally called beam intensity or fluence.

LAIR: Letterman Army Institute of Research

Lambertian surface: an ideal diffuse surface whose emitted or reflected radiance (brightness) is independent of the viewing angle

Laser (Light Amplification by Stimulated Emission of Radiation): a source of intense, collimated, coherent, and monochromatic radiation

Laser device: a device usually composed of an energy source (pumping or excitation medium), an active lasing medium, a feedback mechanism, and an output coupler

Laser system: an assembly of electrical, mechanical, and optical components which includes a laser. This term is generally used to describe a complete system, including the laser device, the pointer tracker (beam control) subsystem, and acquisition and fire control subsystems.

LIDAR: Light Detection and Ranging

Light: see visible radiation.

Linewidth: the frequency or wavelength range over which most of the laser beam's energy is distributed, also called bandwidth or spectral bandwidth.

Liquid laser: see dye laser.

MACOM: Major Army Command

Micron (μ): sometimes used in lieu of micrometer, a unit length equal to 10^{-6} meters

Micrometer (μm): a unit of length equal to 10^{-6} meters, (preferred over the term micron)

MILES: Multiple, Integrated Laser Engagement System

Mode-locking: a technique used to produce high energy laser output of extremely short pulse duration (on the order of picoseconds)

Monochromatic: a term describing the time coherence of light waves having the same wavelengths, commonly used interchangeably with coherent. See coherent light.

NAAQS: National Ambient Air Quality Standard

Nanometer (nm): a unit of length equal to 10^{-9} meters, one-billionth of a meter

NASA: National Aeronautics and Space Administration

Neodymium YAG (Nd: YAG) Laser: a solid-state, flash-pumped laser which uses a neodymium YAG compound as the lasing medium. Wavelength: 1.06 μm (near - IR). YAG is an acronym for Yttrium Aluminum Garnet.

NEPA: National Environmental Policy Act of 1969.

Nominal ocular hazard distance (NOHD): The NOHD is the distance from the operating laser at which the radiant exposure or irradiance within the beam equals the applicable exposure limit.

On-axis: the exact centerline of a sight picture, used as a reference line from which to measure degrees off-axis

Optical density (OD): a logarithmic expression for the attenuation produced by an attenuating medium, such as an eye protection filter.

Optical materials: common materials for lenses and cover plates, including glasses, plexiglass, and quartz for visible light, and germanium for certain sensors

Optically pumped lasers: a type of laser that derives energy from another optical radiation source such as a xenon flash lamp (coherent light sources have also been used)

Optical radiation: electromagnetic wavelengths between 100 nm and 1mm

PAR: photosynthetically active radiation

Photon: a massless "particle" of electromagnetic radiation, with energy equal to hc/λ, where h is Planck's constant (6.63×10^{-34} joule-second) and c/λ is the frequency of the radiation (speed of light divided by wavelength)

Picosecond: a unit of time equal to 10^{-12} seconds, one thousand-billionth of a second

Point source: ideally, a source with infinitesimal dimensions, practically, a source of radiation whose dimensions are small compared with the viewing distance

Pulse repetition rate (PRR): also called pulse repetition frequency (PRF), the number of pulses emitted per unit time

Pulse repetition time (PRT): the reciprocal of the pulse repetition rate (PRR) PRT PRF^{-1}, the period or time duration between the beginning of two pulses

Pulsed laser: a laser that delivers its energy in short pulses, as distinct from a CW laser. A laser that emits for less than 0.25 sec.

Q-switched (Q-spoiled): "Q" stands for quality factor and is a carryover from terminology used in electronic theory. This is a way to produce short pulses (of nanosecond duration) by spoiling the laser optical cavity until sufficient energy is built up in the population inversion. The Q switching "gate" is then opened, allowing an enormous burst of energy to be released in an extremely short period of time.

R&D: Research and Development

Radian: a unit of angular measure equal to the angle subtended at the center of a circle by a chord whose length is equal to the radius of the circle (2.5 radians = 360°)

Radiance: radiant flux or power output per unit solid angle per unit area, expressed in watts per steradian per square centimeter ($W/sr/cm^2$)

Radiant energy: energy which is in the form of electromagnetic waves

Radiant exposure: the total incident energy per unit surface as a per unit of time interval. It is used to express exposure to pulsed laser radiation and is commonly expressed in j/cm^2, also called fluence.

Radiant flux or radiant power: the time rate of flow of radiant energy, usually expressed in watts (one watt = one joule per second)

Radiant intensity: the strength or radiant power of a source in a given direction - radiant flux emitted from the source per unit solid angle (steradian) in the direction of propagation, usually expressed in W/sr, also called brightness

Rangefinder: A device which measures reflection times of a laser beam to determine distances between laser source and target

RCRA: Resource Conservation and Recovery Act of 1976.

Red laser: a laser operating in the visible red band, typically a ruby laser

Reflectance or reflectivity: the ratio of reflected radiant power to incident radiant power

Repetitively pulsed laser: a laser with recurring pulsed output. Repetitively pulsed lasers have properties similar to CW lasers if the PRF, or duty cycle, is very high.

Scattering: deflection of light by atoms, molecules and small particles whose size is near the wavelength of light

Scintillation: a term frequently used to describe the effect upon a laser beam by atmospheric turbulence

Semiconductor: laser (inject diode laser). See diode laser.

Shield: a mechanism to prevent electromagnetic energy from entering and/or leaving a specific place

Solid state laser: a laser which uses a doped crystal or glass as the lasing medium

Speckle: the shimmering granular appearance of laser light reflected from a diffuse surface

Specular reflection: the reflection of light from a very smooth (mirror-like) surface

Steradian: a unit of measure equal to the solid angle subtended at the center of a sphere by an area equal to the radius squared on the surface of the sphere. (The total solid angle of a sphere is 4 steradians).

Strehl ratio: a measure of beam quality expressed as the ratio of the actual beam intensity at the target to the theoretically perfect beam intensity at the target. A perfect beam would have a strehl ratio of one.

TEM: transverse electromagnetic mode

Transmissivity: a measure of the portion of radiation that passes through an optical material. Wavelength dependent.

Transmittance: the ratio of total transmitted radiant power to total incident radiant power

TSCA: Toxic Substances Control Act of 1976.

Turbulence: swirling of air causing refractive index variations which defocus or bend parts of the beam (e.g., shimmering of an image above a hot street)

Ultraviolet radiation (UV): electromagnetic radiation with wavelengths between soft x-rays and visible violet light, often broken down into UV-A (315-400 nm), UV-B (280-315 nm), and UV-C (10-280 nm)

Visible radiation: electromagnetic radiation which can be detected by the human eye. It is commonly used to describe wavelengths which lie in the range between 400 and 700 nm (0.4 to 0.7 μm).

Watt (w): a unit of power, or radiant flux. One watt equals 1 joule per second.

Watt/cm^2: a unit of irradiance used in measuring the amount of power per unit area of absorbing surface, or per area of CW laser beam

Wavelength: The distance between two points in a periodic wave which have the same phase is termed one wavelength. The speed of light (3×10^{10} cm/s) divided by frequency (in Hz) equals wavelength (in cm).

WSMR: White Sands Missile Range

YAG: Yttrium Aluminum Garnet. Slang for Nd: YAG laser.

APPENDIX C

Laser Hazards: Classification and Standards

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LASER HAZARD CLASSIFICATION

C-1. General. Classification of essentially all lasers requires the following radiometric parameters:

a. Wavelength(s) or wavelength range

b. For CW or repetitively pulsed lasers: average power output and limiting exposure duration inherent to the design of the laser or laser system, T_{max}

c. For pulsed lasers: total energy/pulse (or peak power), pulse duration, PRF, and emergent beam radiant exposure.

C-2. Extended Source Lasers. Classification of extended-source lasers or laser systems, such as injection laser diodes, diode arrays, and those lasers having a permanent diffuser within the output optics, requires in addition to the parameters listed in paragraph C-1 the laser source radiance or integrated radiance and the maximum viewing angular subtense.

C-3. Exempt Laser Output Power (P_{exempt}) or Exempt Laser Output Energy (Q_{exempt}). In a "worst-case" analysis of a laser's potential for producing injury, it is necessary to consider not only the laser output irradiance or radiant exposure, but also whether a hazard would exist if the total laser output were concentrated within the defining aperture for the applicable protection standard. For instance, the unfocussed beam of a far-infrared CW laser would not normally be hazardous if the beam irradiance were less than 0.1 $W \cdot cm^{-2}$; however, if the output power were 100 W and the beam were focused at some location to a 1 mm spot, a serious hazard could exist. These terms must be defined in two different ways depending upon whether or not the laser itself is considered an "extended source" (an unusual case):

a. For most lasers P_{exempt} and Q_{exempt} are each the product of:

(1) The intrabeam protection standard for the eye (table B-1) for the limiting exposure duration T max, and

(2) The circular area of the defining aperture for the protection standard (table B-1), in cm^2

b. For extended-source lasers (e.g. laser arrays, laser diodes, and diffused-output lasers) which emit in the spectral range of 0.4 to 1.4 μm, P_{exempt} and Q_{exempt} are determined by that power or energy output such that the source radiance does not exceed the protection standard (table B-2) if the source were viewed at the minimum viewing distance through a theoretically perfect optical viewing system with an entrance aperture of 8 cm which collected the entire laser beam output and which had a 7mm exit pupil. If this definition is difficult to apply, the definition in *a* above may be applied and will result in a conservative P_{exempt} or Q_{exempt}.

C-4. Classification of Multiwavelength Lasers. The classification of laser devices which can potentially emit at numerous wavelengths shall be based on the most hazardous possible operation.

C-5. Laser Device Hazard Classification Definitions. *a. Class I—Exempt Laser Devices.* Any laser device that cannot emit laser radiation levels in excess of P_{exempt} or Q_{exempt} for the maximum possible duration inherent to the design of the laser or laser system. The exemption from hazard controls strictly applies to emitted laser radiation hazards and not to other potential hazards.

b. Class II—Low Power Visible Laser Devices.

(1) Visible (400 nm to 700 nm) CW laser devices which can emit a power exceeding P_{exempt} for the maximum possible duration inherent to the design of the laser or laser system (0.4 μW—for T_{max} greater than 10^4 seconds), but not exceeding 1 mW.

(2) Visible (400 nm to 700 nm) repetitively pulsed laser devices which can emit a power exceeding the appropriate P_{exempt} for the maximum possible duration inherent to the design of the laser device but not exceeding P_{exempt} for a 0.25 s exposure.

c. Class III—Medium Power Laser Devices.

(1) Infrared (1.4 μm—1 mm) and Ultraviolet (200 nm to 400 nm) laser devices which can emit a radiant power in excess of P_{exempt} for the maximum possible duration inherent to the design of the laser device but cannot emit an average radiant power of 0.5 W or greater for T_{max} greater than 0.25s, or a radiant exposure of 10 $J \cdot cm^{-2}$ within an exposure time of 0.25 s or less.

(2) Visible (400 nm to 700 nm) CW or Repetitive Pulsed Laser Devices producing a radiant power in excess of P_{exempt} for a 0.25 s exposure (1 mW for a CW laser), but cannot emit an average radiant power of 0.5 W or greater for T_{max} greater than 0.25 s.

(3) Visible and Near-infrared (400 nm to 1400 nm) Pulsed Laser Devices which can emit a radiant energy in excess of Q_{exempt} but which cannot emit a radiant exposure that exceeds that required to produce a hazardous diffuse reflection as given in table D-1.

(4) Near-infrared (700 nm to 1400 nm) CW Laser Devices or Reptitively Pulsed Laser Devices which can emit power in excess of P_{exempt} for the maximum duration inherent in the design of the laser

device, but cannot emit an average power of 0.5 W or greater for periods in excess of 0.25 s.

d. Class IV—High Power Laser Devices.

(1) Ultraviolet (200 nm to 400 nm) and Infrared (1.4 μm—1 mm) Laser Devices which emit an average power of 0.5 W or greater for periods greater than 0.25 s, or a radiant exposure of 10 J·cm^{-2} within an exposure duration of 0.25 s or less.

(2) Visible (400 nm to 700 nm) and Near-Infrared (700 nm to 1400 nm) Laser Devices which emit an average power of 0.5 W or greater for periods greater than 0.25 s, or a radiant exposure in excess of that required to produce a hazardous diffuse reflection as given in Table D—1.

e. Class V—Enclosed Laser Devices. Any class II, III, or IV laser devices which, by virtue of appropriate design or engineering controls, cannot directly irradiate the eye with levels which are in excess of P_{exempt} or Q_{exempt}.

C-6. Examples. Tables C-1 and C-2 provide examples of hazard classification for some typical lasers.

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8. General Hazard Controls For Laser Radiation.

a. Hazard controls vary depending on the type of laser being used and the manner of its use. Most control measures depend upon the laser classification as specified in appendix C. In general, a class I laser device is one that is considered to be incapable of producing damaging optical radiation levels and is, therefore, exempt from any control measures or other forms of surveillance. A class II Laser device may be viewed directly, but must have a cautionary label affixed to the device warning against continuous intrabeam viewing (staring into the beam).

A class III medium power laser device requires control measures that shall prevent intrabeam viewing. A class IV High Power Laser Device requires the use of controls which shall prevent exposure of the eye and skin to the direct and diffusely reflected beam and the termination of the unused beam (s) by fire-resistant backstops. Class V Enclosed Laser Devices are either class II, class III or class IV lasers contained in a protective housing and operated in such a manner as to be incapable of emitting hazardous radiation from the enclosure. Only a stringent control system permits a laser to qualify as class V

b. It must be remembered that the classification scheme given in paragraph 7*b* relates specifically to the laser device itself and its potential hazard, based on operating characteristics. However, the environment and conditions under which the laser is used, the safety training of persons using the laser and other environmental and personnel factors, may play a role in determining the full extent of hazard control measures. Since such situations will require informed judgements by responsible persons, major responsibility for such judgements should be assigned to a qualified person, namely a Laser Safety Officer. Only properly indoctrinated persons shall be designated Laser Safety Officers or be placed in charge of class III and IV laser installations or operations. The complete enclosure of a laser beam (an enclosed laser) shall be used when feasible. A closed installation provides the next most desirable hazard control measure. Following are details relating to safe laser operation in:—

(1) An outdoor environment where administrative controls often provide the only reasonable approach.

(2) An indoor environment where engineering controls should play the greatest role.

c. Outdoor Laser Installations.

(1) *Class II low power laser devices.* The beam should be terminated where readily feasible at the end of the useful beam path and the laser should not be directed at personnel who are not cognizant of their illumination.

(2) *Class III and IV lasers.*

(*a*) Personnel shall be excluded from the beam path at all points where the beam irradiance or radiant exposure exceed the appropriate Protection Standard. This shall be accomplished by the use of physical barriers, administrative controls, the use of interlocks and by limiting the beam traverse.

(*b*) The tracking of nontarget vehicular traffic or aircraft, whether intentional or inadvertent, shall be prohibited within the calculated hazardous distances of class III or IV lasers.

(*c*) The beam path(s) shall be cleared of all flat specular surfaces capable of producing reflections that are potentially hazardous, or eye protection should be required for all personnel within the hazardous area.

(*d*) Paragraphs 10 and 11 provide detailed guidance applicable to range control of laser rangefinders, illuminators and designators.

(3) *Class IV laser.* Operation of class IV High Power Laser Devices while it is raining or snowing or when there is dust or fog in the air should be avoided without the wearing of laser protective eyewear by personnel within the immediate vicinity of the beam.

Excerpted from

DOCUMENTATION OF THE THRESHOLD LIMIT VALUES

FOURTH EDITION

1980

CINCINNATI, OHIO

AMERICAN
CONFERENCE
OF
GOVERNMENTAL
INDUSTRIAL
HYGENISTS
INC.

LASERS

The Threshold Limit Values (TLVs) are for exposure to laser radiation under conditions to which nearly all workers may be exposed without adverse effects. The values should be used as guides in the control of exposures and should not be regarded as fine lines between safe and dangerous levels. They are based on the best available information from experimental studies.

Limiting Apertures

The TLVs expressed as radiant exposure or irradiance in this section may be averaged over an aperture of 1 mm except for TLVs for the eye in the spectral range of 400-1400 nm, which should be averaged over a 7 mm limiting aperture (pupil); and except for all TLVs for wavelengths between 0.1-1 mm where the limiting aperture is 10 mm. No modification of the TLVs is permitted for pupil sizes less than 7 mm.

The TLVs for *extended sources* apply to sources which subtend an angle greater than α (Table 5) which varies with exposure time. This angle is *not* the beam divergence of the source.

Correction Factors A and B (C_A and C_B)

The TLVs for ocular exposure in Tables 3 and 4 are to be used as given for all wavelength ranges. The TLVs for wavelengths between 700 nm and 1049 nm are to be increased by a uniformly extrapolated factor (C_A) as shown in Figure 2. Between 1049 and 1400 nm, the TLV has been increased by a factor (C_A) of five. For certain exposure times at wavelengths between 550 nm and 700 nm., correction factor (C_B) must be applied.

The TLVs for skin exposure are given in Table 6. The TLVs are to be increased by a factor (C_A) as shown in Figure 2 for wavelengths between 700 nm and 1400 nm. To aid in the determination of TLVs for exposure durations requiring calculations of fractional powers Figures 3, 4, 5 and 6 may be used.

Repetitively Pulsed Lasers

Since there are few experimental data for multiple pulses, caution must be used in the evaluation of such exposures. The protection standards for irradiance or radiant exposure in multiple pulse trains have the following limitations:

(1) The exposure from any single pulse in the train is limited to the protection standard for a single comparable pulse.

(2) The average irradiance for a group of pulses is limited to the protection standard as given in Tables 3, 4, or 6 of a single pulse of the same duration as the entire pulse group.

(3) When the instantaneous Pulse Repetition Frequency (PRF) of any pulses within a train exceeds one, the protection standard applicable to each pulse is reduced as shown in Figure 6 for pulse durations less than 10^{-5} second. For pulses of greater duration, the following formula should be followed:

$$\text{Standard}\begin{pmatrix}\text{single pulse}\\ \text{in train}\end{pmatrix} = \frac{\text{Standard (pulse } n\tau)}{n}$$

where:

n = number of pulses in train
τ = duration of a single pulse in the train
Standard($n\tau$) = protection standard of one pulse having a duration equal to $n\tau$ seconds.

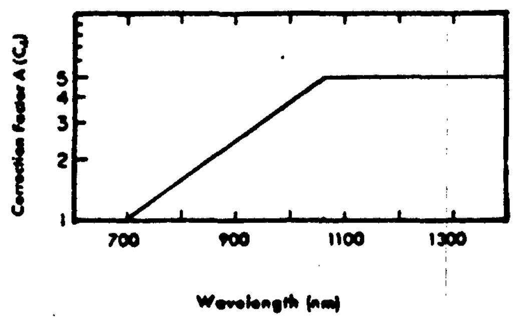

Figure 2 — TLV correction factor for λ = 700 – 1400 nm*

*For λ = 700 – 1049 nm, $C_A = 10^{[illegible]}$
For λ = 1050 – 1400 nm, C_A = 5

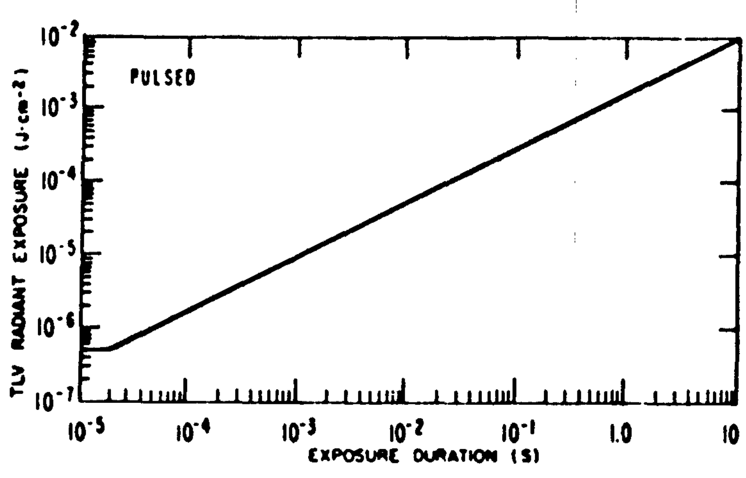

Figure 3a — TLV for intrabeam (direct) viewing of laser beam (400-700 nm).

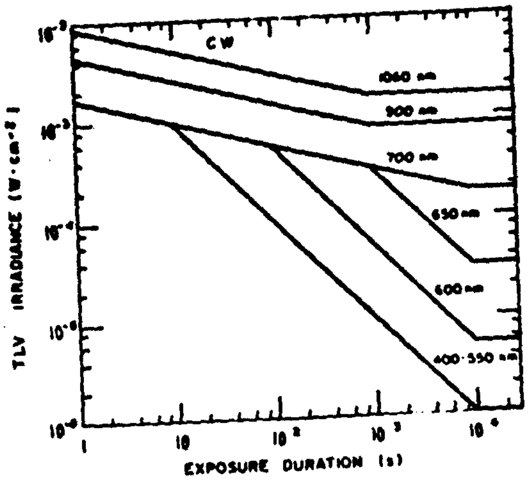

Figure 3b — TLV for intrabeam (direct) viewing of CW laser beam (400-1400 nm)

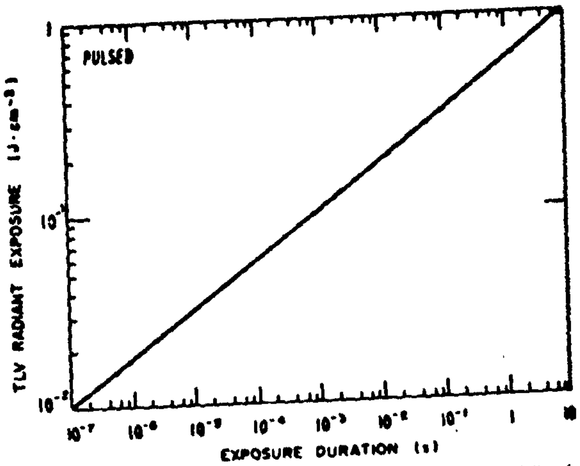

Figure 4a — TLV for laser exposure of skin and eyes for far-infrared radiation (wave-lengths greater than 1.4 μm).

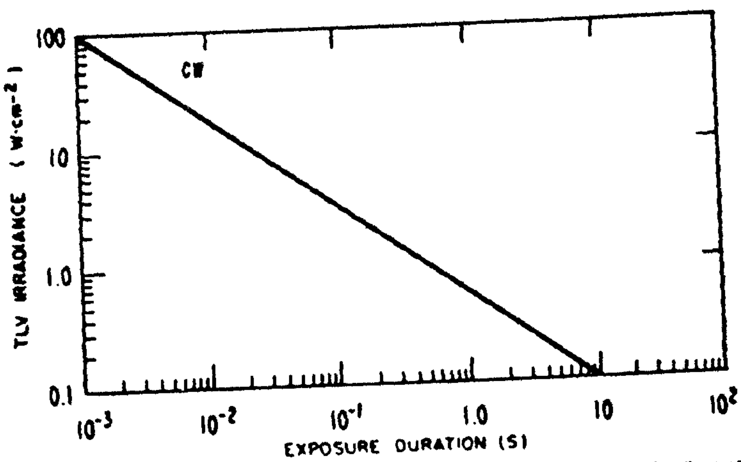

Figure 4b — TLV for CW laser exposure of skin and eyes for far infrared radiation (wavelengths greater than 1.4 μm).

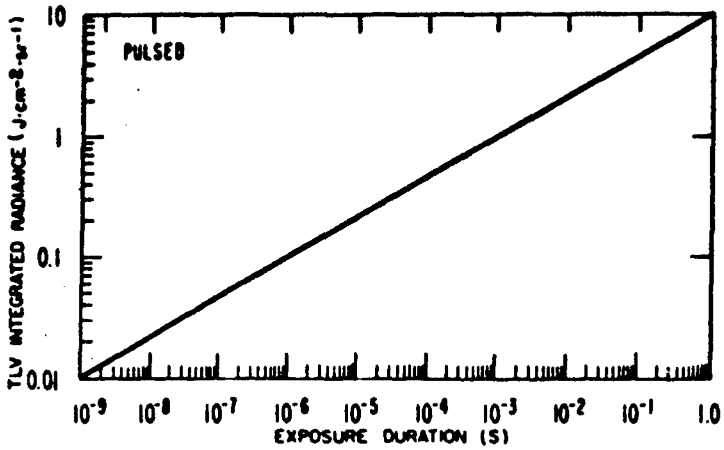

Figure 5a — TLV for extended sources or diffuse reflections of laser radiation (400–700 nm).

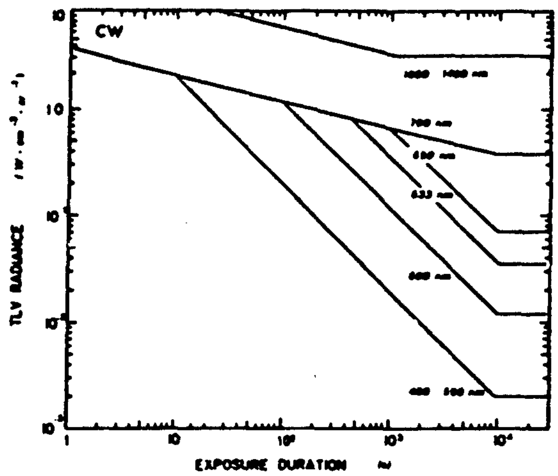

Figure 5b — TLV for intrabeam (direct) viewing of CW laser beam (400–1400 nm).

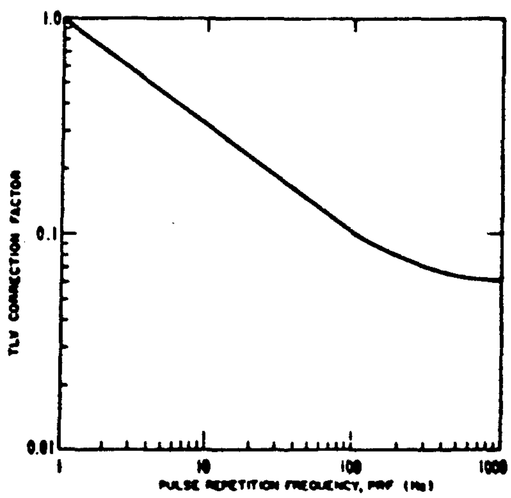

Figure 6 — Multiplicative correction factor for repetitively pulsed lasers having pulse durations less than 10^{-5} second. TLV for a single pulse of the pulse train is multiplied by the above correction factor. Correction factor for PRF greater than 1000 Hz is 0.06.

TABLE 3

Threshold Limit Value for Direct Ocular Exposures (Intrabeam Viewing) from a Laser Beam

Spectral Region	Wave Length	Exposure Time, (t) Seconds	TLV
UVC	200 nm to 280 nm	10^{-9} to 3×10^{4}	3 $mJ \bullet cm^{-2}$
UVB	280 nm to 302 nm	"	3 "
	303 nm	"	4 "
	304 nm	"	6 "
	305 nm	"	10 "
	306 nm	"	16 "
	307 nm	"	25 "
	308 nm	"	40 "
	309 nm	"	63 "
	310 nm	"	100 "
	311 nm	"	160 "
	312 nm	"	250 "
	313 nm	"	400 "
	314 nm	"	630 "
UVA	315 nm to 400 nm	10^{-9} to 10	$.56\, t^{1/4}$ $J \bullet cm^{-2}$
	" "	10 to 10^{3}	1.0 $J \bullet cm^{-2}$
	" "	10^{3} to 3×10^{4}	1.0 $mW \bullet cm^{-2}$
Light	400 nm to 700 nm	10^{-9} to 1.8×10^{-5}	$5 \times 10^{-7} J \bullet cm^{-2}$
	400 nm to 700 nm	1.8×10^{-5} to 10	$1.8\,(t/\sqrt[4]{t})\ mJ \bullet cm^{-2}$
	400 nm to 549 nm	10 to 10^{4}	10 $mJ \bullet cm^{-2}$
	550 nm to 700 nm	10 to T_1	$1.8\,(t/\sqrt[4]{t})\ mJ \bullet cm^{-2}$
	550 nm to 700 nm	T_1 to 10^{4}	$10\, C_B\ mJ \bullet cm^{-2}$
	400 nm to 700 nm	10^{4} to 3×10^{4}	$C_B\ \mu W \bullet cm^{-2}$
IR-A	700 nm to 1049 nm	10^{-9} to 1.8×10^{-5}	$5\, C_A \times 10^{-7} J \bullet cm^{-2}$
	700 nm to 1049 nm	1.8×10^{-5} to 10^{3}	$1.8\, C_A\,(t/\sqrt[4]{t})\ mJ \bullet cm^{-2}$
	1050 nm to 1400 nm	10^{-9} to 10^{-4}	$5 \times 10^{-6} J \bullet cm^{-2}$
	1050 nm to 1400 nm	10^{-4} to 10^{3}	$9\,(t/\sqrt[4]{t})\ mJ \bullet cm^{-2}$
	700 nm to 1400 nm	10^{3} to 3×10^{4}	$320\, C_A\ \mu W \bullet cm^{-2}$
IR-B & C	1.4 μm to 10^{3} μm	10^{-9} to 10^{-7}	$10^{-2} J \bullet cm^{2}$
	" "	10^{-7} to 10	$0.56\,\sqrt[4]{t}\ J \bullet cm^{-2}$
	" "	10 to 3×10^{4}	$0.1\ W \bullet cm^{-2}$

*not to exceed $0.56\, t^{1/4}$ $J \bullet cm^{-2}$ for $t \leq 10$ s.

C_A – See Fig. 2.
$C_B = 1$ for $\lambda = 400$ to 549 nm; $C_B = 10^{0.015(\lambda - 550)}$ for $\lambda = 550$ to 700 nm.
$T_1 = 10$ s for $\lambda = 400$ to 549 nm; $T_1 = 10 \times 10^{0.02(\lambda - 550)}$ for $\lambda = 550$ to 700 n.

TABLE 4

Threshold Limit Values for Viewing a Diffuse Reflection of a Laser Beam or an Extended Source Laser

Spectral Region	Wave Length	Exposure Time, (t) Seconds	TLV
UV	200 nm to 400 nm	10^{-9} to 3×10^{4}	Same as Table 3
Light	400 nm to 700 nm	10^{-9} to 10	$10\,\sqrt[4]{t}\ J \bullet cm^{-2} \bullet sr^{-1}$
	400 nm to 549 nm	10 to 10^{4}	$21\ J \bullet cm^{-2} \bullet sr^{-1}$
	550 nm to 700 nm	10 to T_1	$3.83\,(t/\sqrt[4]{t})\ J \bullet cm^{-2} \bullet sr^{-1}$
	550 nm to 700 nm	T_1 to 10^{4}	$21\, C_B\ J \bullet cm^{-2} \bullet sr^{-1}$
	400 nm to 700 nm	10^{4} to 3×10^{4}	$2.1\, C_B \times 10^{-5}\ W \bullet cm^{-2} \bullet sr^{-1}$
IR-A	700 nm to 1400 nm	10^{-9} to 10	$10\, C_A\,\sqrt[4]{t}\ J \bullet cm^{-2} \bullet sr^{-1}$
	700 nm to 1400 nm	10 to 10^{3}	$3.83\, C_A\,(t/\sqrt[4]{t})\ J \bullet cm^{-2} \bullet sr^{-1}$
	700 nm to 1400 nm	10^{3} to 3×10^{4}	$0.64\, C_A\ W \bullet cm^{-2} \bullet sr^{-1}$
IR-B & C	1.4 μm to 1 mm	10^{-9} to 3×10^{4}	Same as Table 3

C_A, C_B, and T_1 are the same as in footnote to Table 3.

TABLE 5

Limiting Angle to Extended Source Which May Be Used for Applying Extended Source TLVs

Exposure Duration(s)	Angle α (mrad)
10^{-9}	8.0
10^{-8}	5.4
10^{-7}	3.7
10^{-6}	2.5
10^{-5}	1.7
10^{-4}	2.2
10^{-3}	3.6
10^{-2}	5.7
10^{-1}	9.2
1.0	15
10	24
10^{2}	24
10^{3}	24
10^{4}	24

TABLE 6

Threshold Limit Value for Skin Exposure from a Laser Beam

Spectral Region	Wave Length	Exposure Time, (t) Seconds	TLV
UV	200 nm to 400 nm	10^{-9} to 3×10^{4}	Same as Table 3
Light &	400 nm to 1400 nm	10^{-9} to 10^{-7}	$2\ C_A \times 10^{-2}\ J \cdot cm^{-2}$
IR-A	" "	10^{-7} to 10	$1.1\ C_A \sqrt[4]{t}\ J \cdot cm^{-2}$
IR-B & C	1.4 μm to 1 mm	10^{-9} 3×10^{4}	Same as Table 3

C_A = 1.0 for λ = 400–700 nm, see Figure 2 for λ = 700 to 1400 nm.

Documentation for Lasers

Background

A laser (light amplification by the stimulated emission of radiation) is a device which emits electromagnetic radiation having wavelengths in the optical region (100 nm to 1 mm). The radiation emitted by a laser is coherent. Thus, the beam is typically monochromatic and highly collimated in contrast to the output of conventional optical sources.

The eye and skin are critical organs for laser radiation exposure. The type of effect, threshold values, and damage mechanisms vary significantly with wavelength. In addition, the eye is more vulnerable to optical radiation than skin. Consequently, exposure standards have emphasized protection of the eye.

For purposes of specifying this TLV, the optical radiation spectrum has been divided by wavelength into regions as shown in Table 1.

Biologic Effects

UV-C and almost all UV-B radiation is absorbed within the cornea and conjunctiva, whereas UV A radiation is absorbed largely in the lens. Exposure to actinic UV (UV-B and C) laser radiation may lead to the acute effects of corneal photokeratitis (corneal inflammation) and conjunctivitis. Far greater levels of UV-A are required to produce keratitis by a photochemical mechanism. UV-A thermal injury to the lens and cornea is not normally seen at exposure durations greater than 1 ms.[1] The peak sensitivity for corneal injury is believed to be around 270 nm with a drop off in the action spectrum in each direction. Although in the actinic-UV region, the cornea is not substantially more sensitive to injury than untanned caucasian skin, damage to the cornea is much more disabling (and painful) than injury to the skin. And repeated exposure of the cornea does not result in development of natural protection as thickening of the stratum corneum and tanning provides for the skin. Although UV-A is absorbed more heavily in the lens, it is excessive UV-B exposure which is most effective in cataract formation in spite of the very small fraction of UV-B that reaches the lens.[9]

In the visible and IR-A regions (400-1400 nm) the retina is primarily affected. This is due to the transparency of the ocular media and to the inherent focusing properties of the eye. The focusing properties in this region render the

TABLE 1

Regions of the Optical Radiation Spectrum

Region	Wavelength Range
Ultraviolet	100 to 380-400 nm
UV-C	100 to 280 nm
UV-B	280 to 315-320 nm
UV-A	315-320 to 380-400 nm
Light (Visible)	380-400 to 760-780 nm
Infrared (IR)	760-780 nm to 1 mm
IR-A	760-780 nm to 1.4 μm
IR-B	1.4-3.0 μm
IR-C	3.0 μm - 1 mm

retina much more susceptible to damage than any other part of the body. The optical gain in irradiance of the eye is approximately 100,000 for point source. Most of the radiation that reaches the back of the eye is absorbed by the retinal pigmented epithelium (RPE) and by the choroid (which supplies blood to adjacent layers of the retina). The photopigments in the retina absorb only a small fraction of the incident radiation, perhaps less than 5%.

In the IR-B and C regions of the spectrum (≥1.4 μm), the ocular media become opaque as the absorption by water, a major constituent of all biological tissue, is very high in this region. Thus the damage in this infrared region is primarily to the cornea, although lens damage has also been suggested with infrared radiation at wavelengths below 3 μm (IR-A and B). The infrared damage mechanism appears to be thermal, at least for the longer wavelengths. The CO_2 laser at 10.6 μm in its action on all materials containing water exemplifies the thermal nature of the damage. In the IR-C region, as in the ultraviolet, the threshold for damage to the skin is comparable to that of the cornea. However, the damage to the cornea is likely to be of greatest concern.

Rationale for the TLV

To establish a rationale for developing permissible exposure limits from biologic data required a careful analysis of 1) the physical and biologic variables influencing the variability of the laboratory biologic data, 2) the variables influencing the potential for injury in individuals exposed to laser radiation, 3) the increase in severity of injury for supra-threshold exposure doses, 4) the injury mechanism, and 5) the reversibility of injury.[6] Additionally, the accuracy of instruments available for radiometric measurements and the desire for simplicity in expressing the levels have influenced the threshold limit levels. Chronic exposure levels of UV, visible and IR radiation encountered by man in his natural environment were carefully evaluated.[3] When the changing spectrum and angle of incidence of both direct and scattered solar radiation was considered, it was possible to establish TLVs for continuous (15 minute to 8 hours), daily exposure to the eye and skin.

Without an understanding of the mechanisms of injury, there could be no assurance that injurious effects would not appear long after exposure to levels below acute thresholds, perhaps many years following active use of such lasers. The ocular effects are by far the most important, and here delayed effects would probably ensue from chronic exposure of the lens and anterior portion of the eye to UV-B and IR-A radiation. Hence there has been a substantial effort to understand the injury mechanism for each biologic effect in order to judge the possibility of delayed effects.

One of the problems in developing a TLV for any optical radiation is the specification of the limiting aperture over which the level must be measured or calculated. For the skin, where no focusing takes place, one would like to have as small an aperture as possible. Unfortunately, the smaller the aperture, the more sensitive an instrument must be; the greater the potential inaccuracies due to calibration problems; and the more difficult the calculations may be. It was felt that a 1-mm aperture was about the smallest practical size to consider. For continuous exposure conditions, heat flow and scattering in the skin would tend to eliminate any adverse effects of "hot spots" which were smaller than 1 mm. The same arguments hold for exposure of the cornea and conjunctiva to infrared radiation of wavelengths greater than 1.4 μm and ultraviolet wavelengths less than 400 nm. Furthermore, atmospherically induced "hot spots" and the mode structure in multimode lasers seldom account for localized beam irradiances which are limited to areas less than 1 mm in diameter. Another problem appears at wavelengths greater than 0.1 mm. At these far-infrared wavelengths the aperture size of 1 mm begins to create significant diffraction effects and calibration becomes a problem. However, "hot spots" must, by arguments of physical optics, be generally larger than at shorter wavelengths. For this reason we chose an aperture diameter of 1 cm or 11 mm (which has a 1 cm² area) for wavelengths greater than 0.1 mm.

Injury thresholds for both the cornea and the retina vary considerably with wavelength. It was necessary to consider the degree of precision required to track the actual injury threshold variation with wavelength. Normally the solution to this problem was a compromise: the TLVs were adjusted for different wavelengths but in a more simplistic manner than the actual biological data would often suggest.

Figure 2 of the current Laser TLV provides the reciprocal of the product of the relative spectral transmittance of the ocular media and retina absorption, which is an indication of the relative spectral effectiveness of different wavelengths in causing retinal injury.[15,16] However, this curve does not show the relative hazard to the lens of the eye in the near infrared. Thermal injury to the retina resulting from temperature elevation in the retinal pigmented epithelium is the principal effect for exposure durations less than 10 seconds.

Although ambient retinal temperature is important, it is contributory or synergistic rather than the principal factor. When laser exposures occur at several different wavelengths and in different time domains within a given interval, present theories cannot predict the effect of interaction. It would be surprising if there were no interaction, and if each mode acted independently of the others.

All of the known injurious effects have a strong wavelength dependence. Wavelength is especially important in long-term exposures. However, little is well understood about the wavelength relationship in the ultra-short or extremely long time domains.

The TLVs in the far-infrared region were based upon an understanding of the possible thermal effects on the cornea and a knowledge of exposures which have not resulted in adverse effects upon the eye. Because of the lack of accurate data for the infrared laser exposures of the human eye, worst-case exposure conditions were assumed. Specifically, it was assumed that absorption takes place in a very thin layer at the anterior surface of the cornea. This condition is best represented by 10.6 micrometer CO_2 laser exposures. For that matter, it will fit as well exposure of the eye to any wavelength beyond approximately 3 μm. At wavelengths less than 3 μm the radiation penetrates into the cornea more deeply, and significant absorption may take place in the aqueous humor and even the lens.

Little data is available for long term (chronic) exposures to laser radiation. Even exposure to non-laser sources such as bright, small-source lamps and high luminance extended sources has produced insufficient data to allow extrapola-

APPENDIX D

Calculation Aids for Downwind Laser Hazards

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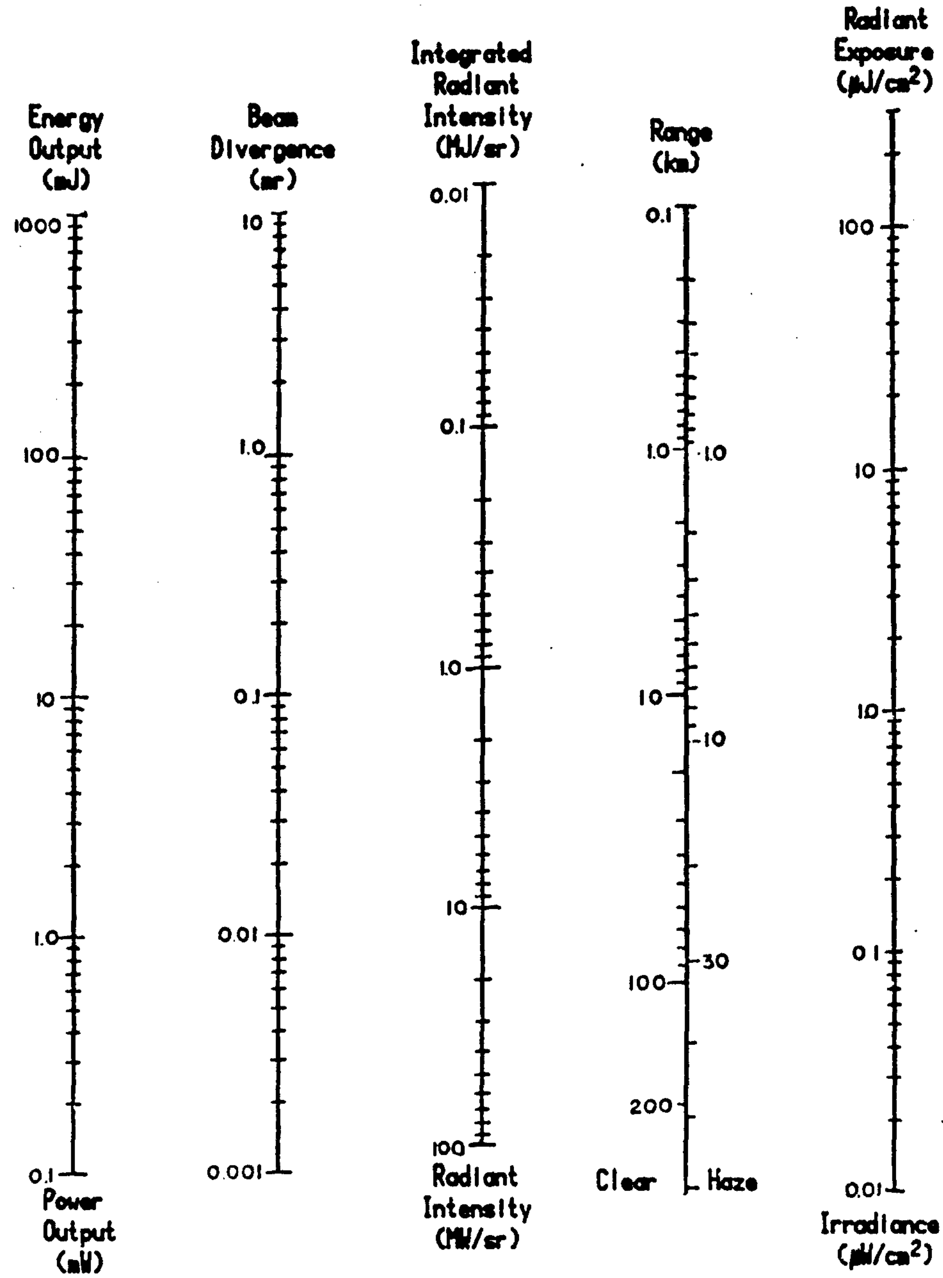
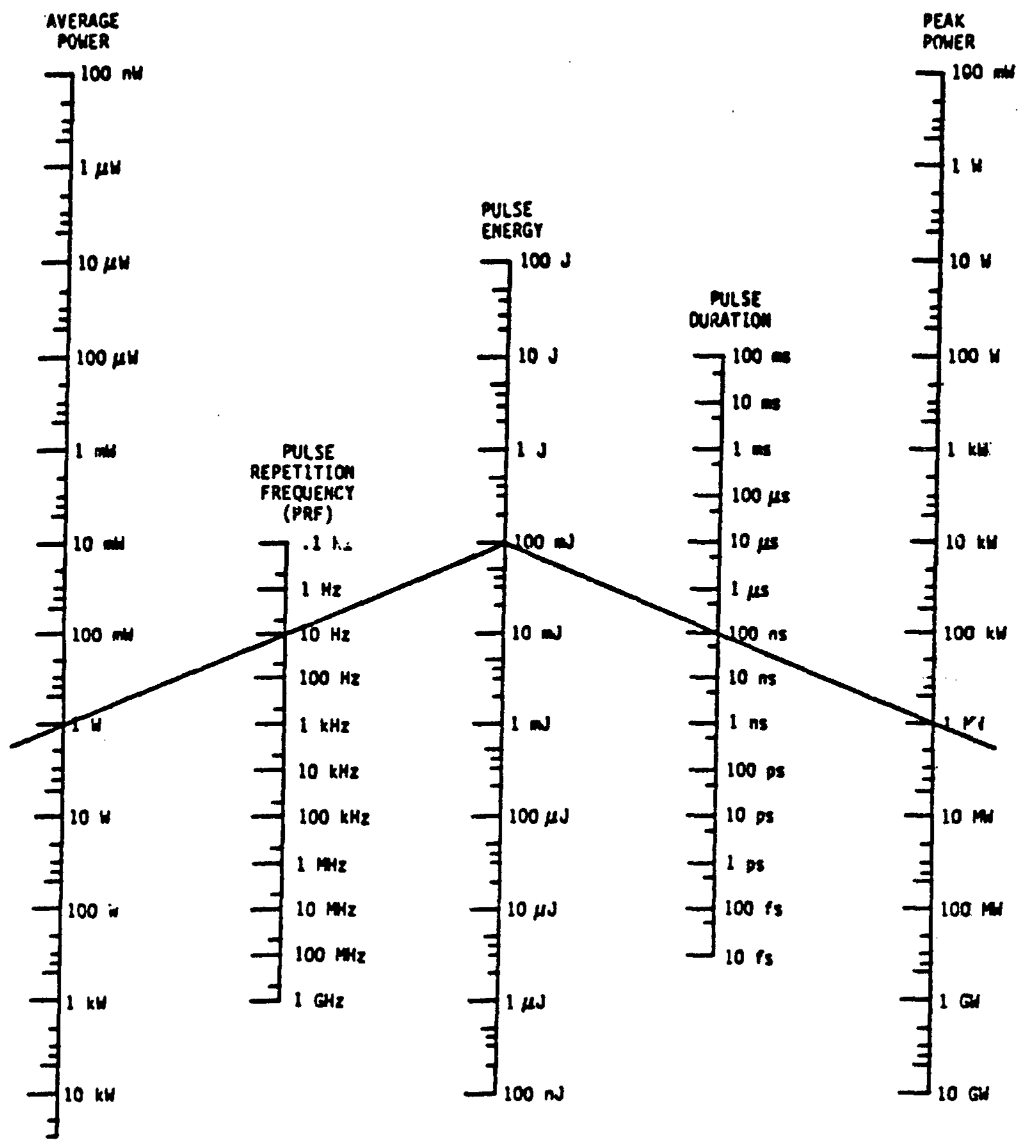
Figure D-1. Nomograph for Downrange Exposures from Laser Radiation*



This nomogram may be used to quickly estimate the hazardous range of most laser devices when output parameters are known. A line is drawn through points corresponding to output energy and beam divergence to extend to radiant intensity line. A second line is extended from the intersection point of the radiant intensity scale through the permissible exposure value (see TB MED 279) to the range scale to provide a hazardous range value for unaided viewing. Atmospheric attenuation is built into the range scale for an attenuation coefficient of 10^{-7} cm^{-1} (clear) and 10^{-6} cm^{-1} (haze).

*excerpted from AEHA Laser Optical Hazards Course Manual, ch. 9 (1979)

Figure D-2 Nomograph for Laser Pulse Energy and Power Conversions



This nomograph relates the energy and power of a laser beam to its temporal characteristics (PRF and pulse duration). For example, the line drawn on the right side of the nomograph shows that a 100-nanosecond pulse containing 100 millijoules has a peak power of 1 Megawatt; the line on the left shows that, for the 100 millijoule pulse, a pulse repetition frequency of 10 hertz corresponds to an average power of 1 Watt.

DETERMINING A LASER BEAM DIAMETER AND DIVERGENCE TO EVALUATE POTENTIAL RADIATION HAZARDS*

1. BACKGROUND. To assess potential health hazards to individuals from exposure to laser radiation requires an understanding of several topics:

a. The shape or profile of the laser beam intensity distribution.

b. How this profile changes as the beam traverses the atmosphere.

c. The defining aperture for the optical radiation protection standards.

2. GAUSSIAN BEAM. The beam profile at a fixed distance from a single-mode laser (often the case for gas lasers) closely resembles a Gaussian distribution. We can express this distribution mathematically for beam irradiance $E(r)$ as a function of radial distance r from the center axis of the beam by:

$$E(r) = E_o e^{-r^2/2\sigma^2} \tag{1}$$

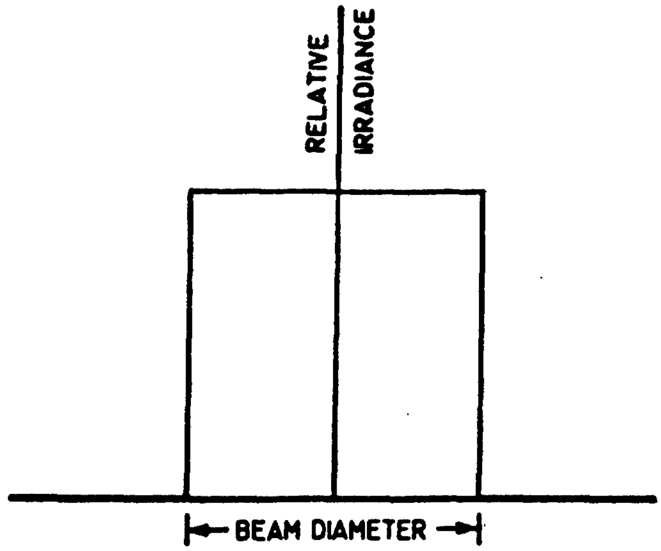
where E_o is the peak irradiance and σ is a constant which is related to the width of the distribution. Normally, the radiant exposure beam profile at the exit of a solid-state pulsed ruby laser system such as from some laser rangefinders does not even remotely follow a Gaussian distribution. At great distances from the laser, however, the beam is "truncated" and broken up into various hot spots. This change in the shape of the beam occurs due to diffraction at the lasers projection optics as well as interactions between the beam and the atmosphere. Measurements of maximal beam irradiance at several points downrange permit the calculation of an effective beam diameter which can be related to σ. Hence, the mathematics of equation 1 could also be used for a pulsed laser system with beam radiant exposure $H(r)$ as a function of radial distance assuming an effective value for σ.

3. BEAM DIAMETER. The diameter of a laser beam is not directly apparent for a Gaussian distribution as opposed to a rectangular beam profile as shown in Figure 1. Laser technologists have defined the beam diameter in different ways. We wish to define the beam diameter such that the peak irradiance can be readily calculated. Consider the total power contained within a beam with radial symmetry. This total power, Φ, is given by the following integral:

$$\Phi = \int_0^\infty E(r)\ 2\pi r\ dr \tag{2}$$

where $2\pi r\ dr$ is the differential area of an infinite diameter circular aperture thru which the beam passes. Combining equations 1 and 2 and integrating we obtain:

*Excerpted from AEHA Laser Optical Hazards Course Manual, ch. 12 (1979)



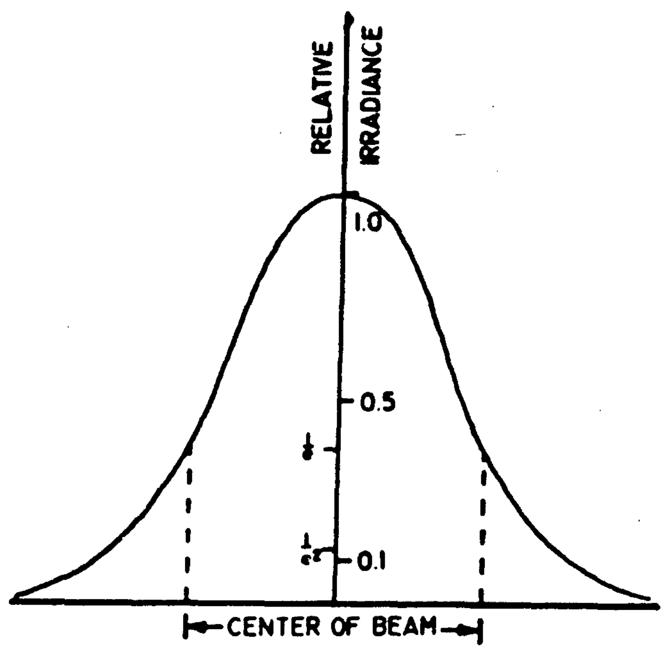


Figure 1. A Gaussian Beam as Illustrated in the Lower Graph has no Clearly Defined Edge as does the Rectangular Beam Profile Illustrated in the Upper Graph.

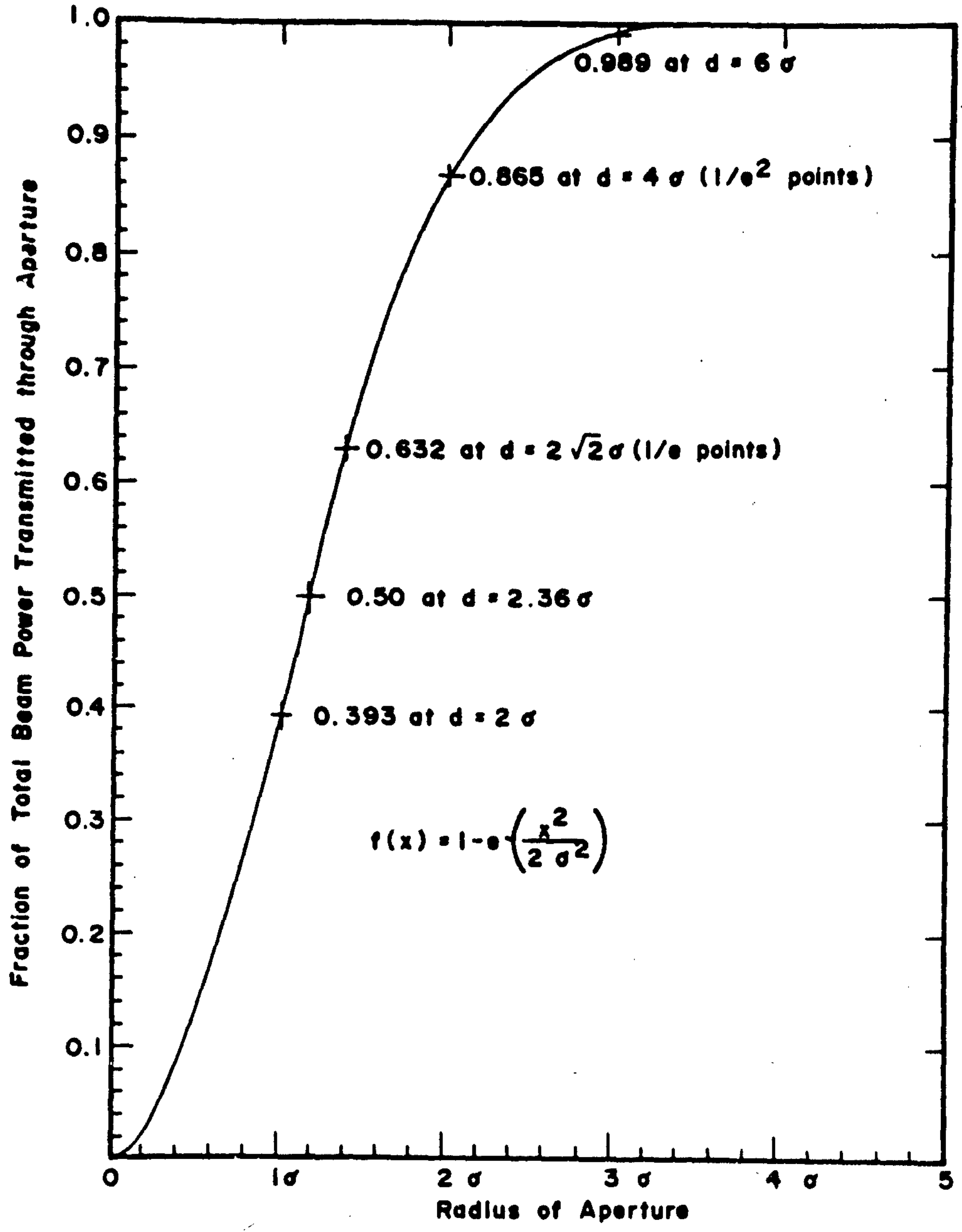


Figure 2. Beam Diameter is Determined by Measuring the Fraction of Total Power in a Gaussian Laser Beam which Passes through a Calibrated Aperture. If 63 Percent of the Beam Passes through an Aperture of Diameter, d, then d is the Diameter at 1/e Points. The Diameter at 1/e Points is 1.2 Times the Aperture that Passes 50 Percent of the Total Beam Power.

device, but cannot emit an average power of 0.5 W or greater for periods in excess of 0.25 s.

d. Class IV—High Power Laser Devices.

(1) Ultraviolet (200 nm to 400 nm) and Infrared (1.4 μm—1 mm) Laser Devices which emit an average power of 0.5 W or greater for periods greater than 0.25 s, or a radiant exposure of 10 J·cm^{-2} within an exposure duration of 0.25 s or less.

(2) Visible (400 nm to 700 nm) and Near-Infrared (700 nm to 1400 nm) Laser Devices which emit an average power of 0.5 W or greater for periods greater than 0.25 s, or a radiant exposure in excess of that required to produce a hazardous diffuse reflection as given in Table D—1.

e. Class V—Enclosed Laser Devices. Any class II, III, or IV laser devices which, by virtue of appropriate design or engineering controls, cannot directly irradiate the eye with levels which are in excess of P exempt or Q exempt.

C-6. Examples. Tables C-1 and C-2 provide examples of hazard classification for some typical lasers.

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8. General Hazard Controls For Laser Radiation.

a. Hazard controls vary depending on the type of laser being used and the manner of its use. Most control measures depend upon the laser classification as specified in appendix C. In general, a class I laser device is one that is considered to be incapable of producing damaging optical radiation levels and is, therefore, exempt from any control measures or other forms of surveillance. A class II Laser device may be viewed directly, but must have a cautionary label affixed to the device warning against continuous intrabeam viewing (staring into the beam).

A class III medium power laser device requires control measures that shall prevent intrabeam viewing. A class IV High Power Laser Device requires the use of controls which shall prevent exposure of the eye and skin to the direct and diffusely reflected beam and the termination of the unused beam (s) by fire-resistant backstops. Class V Enclosed Laser Devices are either class II, class III or class IV lasers contained in a protective housing and operated in such a manner as to be incapable of emitting hazardous radiation from the enclosure. Only a stringent control system permits a laser to qualify as class V

b. It must be remembered that the classification scheme given in paragraph 7*b* relates specifically to the laser device itself and its potential hazard, based on operating characteristics. However, the environment and conditions under which the laser is used, the safety training of persons using the laser and other environmental and personnel factors, may play a role in determining the full extent of hazard control measures. Since such situations will require informed judgements by responsible persons, major responsibility for such judgements should be assigned to a qualified person, namely a Laser Safety Officer. Only properly indoctrinated persons shall be designated Laser Safety Officers or be placed in charge of class III and IV laser installations or operations. The complete enclosure of a laser beam (an enclosed laser) shall be used when feasible. A closed installation provides the next most desirable hazard control measure. Following are details relating to safe laser operation in:—

(1) An outdoor environment where administrative controls often provide the only reasonable approach.

(2) An indoor environment where engineering controls should play the greatest role.

c. Outdoor Laser Installations.

(1) *Class II low power laser devices.* The beam should be terminated where readily feasible at the end of the useful beam path and the laser should not be directed at personnel who are not cognizant of their illumination.

(2) *Class III and IV lasers.*

(a) Personnel shall be excluded from the beam path at all points where the beam irradiance or radiant exposure exceed the appropriate Protection Standard. This shall be accomplished by the use of physical barriers, administrative controls, the use of interlocks and by limiting the beam traverse.

(b) The tracking of nontarget vehicular traffic or aircraft, whether intentional or inadvertent, shall be prohibited within the calculated hazardous distances of class III or IV lasers.

(c) The beam path(s) shall be cleared of all flat specular surfaces capable of producing reflections that are potentially hazardous, or eye protection should be required for all personnel within the hazardous area.

(d) Paragraphs 10 and 11 provide detailed guidance applicable to range control of laser rangefinders, illuminators and designators.

(3) *Class IV laser.* Operation of class IV High Power Laser Devices while it is raining or snowing or when there is dust or fog in the air should be avoided without the wearing of laser protective eyewear by personnel within the immediate vicinity of the beam.

$$\Phi = \pi D_L^2 E_o/4 \text{ where } D_L \equiv 2\sqrt{2}\sigma \qquad (3)$$

Physically D_L defines twice the radial distance to where the irradiance on the Gaussian distribution is reduced to E_o/e (or beam diameter to 1/e-peak-irradiance-points). Therefore by knowing the beam diameter defined at 1/e-peak-irradiance-points and the total power contained within the Gaussian profile it is possible to predict the peak irradiance with the same computation as for a rectangular beam. One simple method for experimentally measuring the beam diameter consists of allowing 63 percent or $1 - 1/e$ of the total beam power to pass thru an adjustable circular aperture located on the beam axis. The diameter of this aperture is D_L. (This can be mathematically verified by integrating equation 2 to the beam radius at 1/e-peak-irradiance-points or $\lambda = \sqrt{2}\,\sigma$). Figure 2 is a plot of this integral over various limits of integration.

4. BEAM DIVERGENCE. The profile of this laser beam at any other point along its path will also be approximately Gaussian (assuming that other optical systems are not present which might obstruct the path or in any way modify the beam shape). The Gaussian beam in the far field will widen and the peak irradiance will be reduced as we travel farther from the laser. The total power within the beam will be reduced only slightly due to atmospheric absorption. The beam diameter at some distance, r, from the laser is given by:

$$D_L = r \tan \phi + a \qquad (4)$$

where ϕ is the beam divergence and a is the diameter to 1/e peak-irradiance-points at the laser output. Since most laser systems are highly collimated we obtain from equation 4:

$$D_L \approx r\phi + a \qquad (5)$$

From this expression it is apparent that the beam divergence must also be specified to 1/e-peak-irradiance-points. To demonstrate this consider specifying the beam diameter to $1/e^2$-peak-irradiance-points (D^1) then from equation 1 we can prove that:

$$D_L = D^1/\sqrt{2} \qquad (6)$$

and equivalently:

$$a = a^1/\sqrt{2} \qquad (7)$$

Therefore we find that:

$$\phi = \phi^1/\sqrt{2} \qquad (8)$$

where a^1 and ϕ^1 are the exit beam diameter and divergence respectively defined to $1/e^2$-peak-irradiance.

The laser range equation is obtained by combining equations 3 and 5 or:

$$E(r) = (1.27 \, \Phi \, e^{-\mu r})/(a + r\phi)^2 \qquad (9)$$

where $e^{-\mu r}$ is the atmospheric transmission. (μ is called the atmospheric attenuation coefficient and is normally very small.) Hence, although beam divergence could be defined in several ways, it is convenient for a hazard evaluation to select the beam divergence defined at 1/e-peak-irradiance-points so that it is possible to predict the peak irradiance within a Gaussian profile at any distance from a laser of known output power. We can also apply this equation to experimentally measure the beam divergence. We can measure the peak irradiance with a detector whose sensitive diameter is much smaller than D_L for the beam in the far field of the laser ($r\phi >> a$) and them compute ϕ from equation 9 since Φ, μ, r and a can also be measured.

5. PROTECTION STANDARDS. Why does one need to calculate the peak irradiance in the beam? We do not always need the peak irradiance but normally the beam diameter, D_L, is much larger than the sampling diameter for the laser protection standards since the potential hazard often extends to great distances from the laser. The protection standards for the skin and cornea and lens of the eye are based upon power or energy transmitted through a 1-mm aperture (for wavelengths between 10^5 and 10^6 nm this aperture becomes 10 mm) whereas the aperture for the "retinal hazard region" of the spectrum (400 to 1400 nm) is based upon a 7-mm aperture (dark adapted pupilary diameter). Actual range measurements are performed on laser systems with small exit beam diameters using an appropriate diameter aperture placed directly in front of the detector and centered on the beam axis.

6. RELATIVE BEAM POWER OR ENERGY. The maximum power or energy available to pass thru the appropriate defining aperture (for the various protection standards) is the most useful parameter to determine from the standpoint of evaluating optical radiation hazards. Figure 2 can be used to relate the fraction of total power transmitted thru different diameter apertures when the total beam power is known. Expressed mathematically Figure 2 simply states that the power thru an arbitrary axial aperture of diameter d is:

$$\Phi d = \Phi(1-\beta) \qquad (10)$$

where $\beta = E(d/2)/E_o$ and $d = 2\sigma\sqrt{2\ell n(1/\beta)}$.

By integrating the Gaussian profile over the area of an arbitrary circular aperture and combining this power with equation 3 we obtain another useful expression:

$$\Phi d = \Phi[1-e^{(d/D_L)^2}] \quad (11)$$

Hence a general laser range equation can be seen from equation 11 which could be applied to laser systems which have relatively short retinal hazardous ranges (D_L is of the same order of magnitude as 7 mm) or to telescopic viewing of such beams. The average irradiance over an arbitrary axial circular aperture of diameter d is given by:

$$E(r,d) = 2.6\Phi[1-e^{(d/D_L)^2}]e^{-\mu r} \quad (12)$$

This range equation is primarily applied to low power Ga-As laser diodes and He-Ne lasers.

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APPENDIX E

Bibliography of USAEHA Health Hazard Analyses of Laser Systems and High Intensity Lights

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The following listing of analyses of laser health hazards were excerpted from the current (1981) Laser and Optical Hazards Course Manual prepared by the US Army Environmental Hygiene Agency, Aberdeen Proving Ground, MD 21010.

This manual is also the source of a comprehensive (more than 2400 references, 183 pages) laser hazards bibliography. Readers interested in obtaining copies of this bibliography should address inquiries to: Commander, US Army Environmental Hygiene Agency, Directorate of Radiation and Environmental Services, ATTN: HSE-RL, Aberdeen Proving Ground, MD 21010.

ABBREVIATED LISTING OF USAEHA HEALTH HAZARD ANALYSES OF LASER SYSTEMS AND HIGH INTENSITY LIGHTS

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42-42-68/69	Laser Rangefinder XE-8, US Army Artillery Board, Fort Sill, Oklahoma	AD861662
42-48-68/69	Laser Rangefinder AN/VVS-1 M-60 Tank Laser Rangefinder-Engineering Development Model, Aberdeen Proving Ground, Maryland	AD861655
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42-007-69	AN/MSS-3 Xenon Searchlight (2.2 kW) Fort Belvoir, Virginia, July - September 1968	AD861652
42-027-69	PDSI Night Vision Illuminator, US Army Night Vision Laboratory (USANVL), Fort Belvoir, Virginia, 4 September 1968	AD861653
42-032-69/70	Evaluation of Direct Fire Simulator (DFS), Part I - Preliminary Evaluation Rifle-Mounted Gallium-Arsenide Laser Transmitter, March and June 1968	AD861664
42-035-69	Evaluation of AN/TVS-3 Searchlight (20 kW), January - Arpil 1969	AD861654
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42-089-69/70	Evaluation of a Laser Cane, May - July 1969	AD861666
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42-014-71	US Army Topographic Command Optical Distance Measuring Equipment, AGA Model 4D Geodimeter, February - April 1971	AD729345
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42-048-71	Evaluation of the LS-59A Airborne Flasher Unit	AD883422
42-072-71/72	Evaluation of Prototype Anti-Laser Goggles, Part II - Coverall Goggles (Type II and III)	AD889115
42-073-71	Laser Distance Measuring Equipment Used by US Army Topographic Command (USATOPOCOM) February - April 1971	AD729346
42-086-71/72	Laser Tank Gunnery Trainer (LTGT) Device 3A110, November - December 1971	AD891946
42-119-71/72	Large Gun Direct Fire Simulator	AD889401
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42-028-72	Dragon Tracker Eye Protection Filters, October 1971	AD889942
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42-012-73/74	Laser Hazard Controls for Tank Ranges, Fort Knox, Kentucky, 14 July 1972 - 12 May 1973	AD912647
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42-016-74	Evaluation of Laser Rangefinder/Designator Northrop ISTAR Mark II Systems, Hunter-Liggett Military Reservation, Jolon, California, October 1973	AD915921L

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42-058-76	Evaluation of Training Problems with Tactical Lasers, January - July 1976	ADA030039
42-098-76	Hazard Evaluation of the Laser Rangefinder of the XM-1 Tank Candidate System of Chrysler Corp, April 1976	ADB017322L
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